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McGraw-Hill Machining and Metalworking Handbook

Third Edition

- Rapid prototyping
- Process optimization
- Product development
- CAD/CAM/CAE

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Chapter

1

Modern Metalworking Machinery, Tools, and Measuring Devices

Metalworking machinery, tools, and measuring instruments have advanced considerably over the past 50 years. This chapter will show some of the new machines, tools, and instruments used throughout industry today that allow us to produce parts faster and more accurately than was possible in the past. The widespread use and implementation of microprocessors to control the actions of metalworking machinery is evident in many of the photographs of modern equipment shown in this chapter. Photographs of other modern metalworking machinery appear throughout this *Handbook*.

1.1 Metalworking Process Overview

When a metal part is fabricated, the part blank either can come from a near-net-shape manufacturing process or it can come in the form of bars, rods, plates, etc. Metal casting processes such as die casting, sand casting, and investment casting are the most common methods of producing a part blank that is close to its final shape (i.e., near net shape). Recent years also have seen a flood of new solid freeform fabrication (SFF) processes that are capable of directly producing near-net-shape functional metal parts without the need for molds, dies, etc. (see Chap. 10). In the case of near-net-shape processes, rough

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machining of large amounts of stock is not necessary. Instead, it is only necessary to finish machine those features that are critical to the function of a part.

1.1.1 Primary processes

Die casting. Small or medium-sized parts in nonferrous alloys such as magnesium, aluminum, and zinc are injected under pressure into a steel die. A machining allowance of 0.25 to 0.5 mm (0.010 to 0.020 in) for critical features is typical.

Sand casting. Molten metal is cast into a packed-sand mold. Parts weighing from just a few ounces to several tons can be sand cast. The most commonly sand-cast metals include irons, stainless steels, aluminum, and nickel alloys. Since the surface of the cast part is textured, a machining allowance typically is provided for critical features. Recommended machining allowances for a variety of metals are provided in Table 1.1.

Investment casting. Both ferrous and nonferrous metals may be investment cast into a single-use refractory ceramic mold. High-temperature-reactive metals such as titanium typically are vacuum investment cast.

Forging. Metals such as nonferrous alloys (e.g., aluminum, magnesium, and brass), steels, and nickel alloys are relatively easy to forge. The slugs are essentially hammered by a die such that the metal deforms to the shape of the die. Recommended machining allowances for a variety of metals are provided in Table 1.2.

Powder metallurgy. Metal powder is compacted by a die and then sintered to hold its shape. The resulting parts are porous and optionally are infiltrated to 100 percent density.

Extrusion. A heated billet is forced through a die opening such that the length of the billet takes on the cross-sectional shape of the die opening.

1.1.2 Metal-cutting processes

CNC machining. The two most versatile machines in the modern machining industry are the computer numerical control (CNC)

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TABLE 1.1 Sand Casting Allowances for Each Side

		Allowance, mm (in)	
	Casting size, mm (in)*	Drag and sides	Cope surface
Gray iron	Up to 150 (up to 6)	2.3 (3/32)	3 (1/8)
	150–300 (6–12)	3 (1/8)	4 (5/32)
	300–600 (12–24)	5 (3/16)	6 (1/4)
	600–900 (24–36)	6 (1/4)	8 (5/16)
	900–1500 (36–60)	8 (5/16)	10 (3/8)
	1500–2100 (60–84)	10 (3/8)	13 (1/2)
	2100–3000 (84–120)	11 (7/16)	16 (5/8)
Cast steel	Up to 150 (up to 6)	3 (1/8)	6 (1/4)
	150–300 (6–12)	5 (3/16)	6 (1/4)
	300–600 (12–24)	6 (1/4)	8 (5/16)
	600–900 (24–36)	8 (5/16)	10 (3/8)
	900–1500 (36–60)	10 (3/8)	13 (1/2)
	1500–2100 (60–84)	11 (7/16)	14 (9/16)
	2100–3000 (84–120)	13 (1/2)	19 (3/4)
Malleable iron	Up to 75 (up to 3)	1.5 (1/16)	2.3 (3/32)
	75–300 (3–12)	2.3 (3/32)	3 (1/8)
	300–450 (12–18)	3 (1/8)	4 (5/32)
	450–600 (18–24)	4 (5/32)	5 (3/16)
Ductile iron	Up to 150 (up to 6)	2.3 (3/32)	6 (1/4)
	150–300 (6–12)	3 (1/8)	10 (3/8)
	300–600 (12–24)	5 (3/16)	19 (3/4)
	600–900 (24–36)	6 (1/4)	19 (3/4)
	900–1500 (36–60)	8 (5/16)	25 (1)
	1500–2100 (60–84)	10 (3/8)	28 (1 1/8)
	2100–3000 (84–120)	11 (7/16)	32 (1 1/4)
Nonferrous metals	Up to 150 (up to 6)	1.6 (1/16)	2.3 (3/32)
	150–300 (6–12)	2.3 (3/32)	3 (1/8)
	300–600 (12–24)	3 (1/8)	4 (5/32)
	600–900 (24–36)	4 (5/32)	5 (3/16)

**Casting size* refers to the overall length of the casting and not to the length of a particular measurement.

SOURCE: Bralla, J., *Design for Manufacturability Handbook.* New York: McGraw-Hill, 1999.

milling machine (Fig. 1.1) and the CNC lathe (Fig. 1.2). A key to the versatility of these machines is the automatic tool changer. Vertical machining centers (VMCs) such as the one shown in Fig. 1.1 include a carousel that holds many different cutting tools such as milling cutters, drills, reamers, and taps. The automatic tool changer changes cutting tools between machining operations without any

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TABLE 1.2 Typical Machining Allowances for Forgings

Alloy family	Forging size: Projected area at parting line, mm (in)		
	To 640 cm^2 (100 in^2)	To 2600 cm^2 (400 in^2)	Over 2600 cm^2 (400 in^2)
Aluminum	0.5–1.5 (0.020–0.060)	1.0–2.0 (0.040–0.080)	1.5–3.0 (0.060–0.120)
Magnesium	0.5–1.5 (0.020–0.060)	1.0–2.0 (0.040–0.080)	1.5–3.0 (0.060–0.120)
Brass	0.5–1.5 (0.020–0.060)	1.0–2.0 (0.040–0.080)	1.5–3.0 (0.060–0.120)
Steel	0.5–1.5 (0.020–0.060)	1.5–3.0 (0.060–0.120)	3.0–6.0 (0.120–0.240)
Stainless steel	0.5–1.5 (0.020–0.060)	1.5–2.5 (0.060–0.100)	1.5–5.0 (0.060–0.200)
Titanium	0.8–1.5 (0.030–0.060)	—	2.0–6.0 (0.080–0.240)
Niobium	0.8–2.5 (0.030–0.100)	—	—
Tantalum	0.8–2.5 (0.030–0.100)	—	—
Molybdenum	0.8–2.0 (0.030–0.080)	2.0–3.0 (0.080–0.120)	—

SOURCE: Bralla, J., *Design for Manufacturability Handbook.* New York: McGraw-Hill, 1999.

user intervention, thus allowing several machining operations to be executed in a single workpiece setup. Likewise, the CNC lathe in Fig. 1.2 incorporates an automatic tool changer that can switch between tools that perform facing, knurling, grooving, boring, and many other turning operations.

Electric discharge machining (EDM). EDM comes in two forms—sinker EDM and wire EDM. Sinker EDM uses spark erosion to machine a workpiece with a graphite or copper electrode whose shape is the negative of the cavity being machined. Wire EDM uses spark erosion with a wire to cut two-dimensional (2D) profiles.

Laser machining. A powerful laser beam coupled with a CNC motion-control system is used to cut 2D profiles in sheet or plate material.

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Figure 1.1 Vertical machining center.

Figure 1.2 CNC lathe.

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Complex, thin parts whose quantity does not warrant a hard die are produced using this method.

Chemical milling. Large masses of metal may be removed effectively in producing a part using the etching action of chemicals. Very thin and delicate parts also may be produced with chemical milling or etching. A tough photoresistive substance covers the parts of the metal that are not to be removed. Printed circuit board production is actually a chemical milling operation.

Waterjet machining. A very high pressure jet of water, loaded with microfine abrasives, is used to cut the sheet or plate material of metal, plastic, glass, or other composition. As is the case with laser machining, waterjet machining is useful when the production volumes do not warrant a hard die. The absence of a heat-affected zone is advantageous as well. Figure 1.3 shows a nested pattern of sheet metal parts being waterjet machined. Figure 1.4 shows a complex geometric shape cut from plate.

Figure 1.3 Waterjet machining operation. *(Image courtesy of OMAX Corporation, www.omax.com.)*

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Figure 1.4 Complex waterjet-machined plate. *(Image courtesy of OMAX Corporation, www.omax.com.)*

1.1.3 Sheet metal parts fabrication methods

Hard dies. A die set is used to stamp out the part in flat pattern. Progressive dies also bend the part into the required shape after it is stamped in flat pattern. This is the most common, economical method devised to mass produce large quantities of parts to great accuracy.

Punch press. Large sheet metal parts may be made to accurate standards using modern computer-controlled automatic multistation punch presses. Programmers write the direct numerical control (DNC) programs for these machines, which are then loaded into the machine's computer or controller. The machine operator starts the program and stands back to watch the machine go through the sequence of operations required to produce the finished part in flat pattern.

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Roll forming. Flat strips of sheet metal are fed into the roll-forming machine, where they progress through a set of sequenced rollers to produce a long sheet metal part of constant cross-sectional shape.

Hydropressing. A sheet metal flat-pattern part is placed on a set of forming dies, being located correctly with locator pins, and is then pressed into shape by the action of the hydropress. Many aircraft sheet metal parts are produced in this manner. Lightening holes and shrink flutes are produced simultaneously with the part to control the metal along curved surfaces.

Hydraulic brakes. In this machine, a flat-pattern sheet metal part is given flanges or webs to produce the finished part. The modern brakes have automatic back gauges and material-handling devices to assist the operator in making the various bends and flanges required on the part.

Hydraulic shears. The standard hydraulic shear cuts sheet metal according to the back gauge set by the machine operator and his or her accuracy in placing the sheet into the machine.

1.2 Measurement and Gauging

The preceding section provided an overview of many types of metalworking and machining processes. In a production environment, parts typically are fabricated according to specifications on the computer-aided design (CAD) drawing using one or more of the aforementioned processes. At certain points during the fabrication process, parts are inspected to verify that they satisfy the required geometric and dimensional tolerances. In some cases, 100 percent of the parts are inspected. In many instances, however, it is sufficient to inspect a subset of parts using a statistical sampling scheme. This section describes some of the instruments used to perform component inspection.

1.2.1 Coordinate measuring machines (CMMs)

CMMs are highly versatile inspection machines. Although CMMs are available in numerous configurations, the typical CMM consists of a probe that is positioned beneath a gantry. Depending on the type

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of CMM, the probe can be moved manually by the operator's hand, or it can be moved automatically via a motion-control system. The workpiece being inspected is rigidly clamped to the CMM's granite table.

In manual mode, the operator tells the computer which feature(s) he or she is going to inspect, and the control computer will then instruct the user as to what points need to be probed for a given feature. To measure the distance between two faces, for instance, the operator must touch the probe to at least three points on the first face (i.e., three points define the plane) and one point on the second face (i.e., the perpendicular distance from a point on the second surface to the plane defined by the three points on the first surface). To measure the diameter of a hole, the user is prompted to touch the probe to three or more points around the perimeter of the hole. For each feature, the CMM control computer prompts the user to touch the probe to the appropriate number of points for the feature being inspected.

Fully automated CMMs are also available. With automated CMMs, the inspection planner starts with the geometric and/or dimensional tolerances (GD&Ts) specified in the CAD model by the mechanical designer. CMM software packages such as *PC-DMIS* are now available that are capable of extracting GD&T specifications from a CAD model. Using this software, the inspection planner identifies each feature in the CAD model to be inspected in a given setup on the bed of the CMM. The software then automatically generates an inspection plan for that setup on the CMM. The process is very much like generating toolpaths for a computer numerical control (CNC) milling machine. In this case, the touch probe rather than a rotating cutting tool automatically follows the prescribed path. After the workpiece has been inspected, the CMM software generates an inspection report. In many instances, companies will store these inspection results in a central database for purposes of traceability.

Both rigid and touch probes are available on CMMs. With a rigid probe, the operator must press a button manually so that the CMM can capture the *x,y,z* coordinates of the probe at that instant. With a touch probe, the probe automatically senses when it has touched the part, and the *x,y,z* coordinates are sent to the control computer immediately. Motorized touch probes are also available that can tilt and swivel in order to inspect features that otherwise would not be accessible in a given setup orientation.

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1.2.2 Handheld measurement and gauging devices

Definitions

Precision. For any measuring device, *precision* is an indication of how much variation one will observe when one measures the same dimension on the same part using the same measuring device. The terms *precision* and *repeatability* are often used interchangeably. The sample standard deviation of multiple measurements taken on the same feature with the same device by the same operator is an indicator of precision. The smaller the standard deviation, the higher is the precision.

Accuracy. *Accuracy* is an indication of how close the measured dimension is to the true value for that dimension. Note that accuracy and precision are not the same thing. A device can be highly precise but very inaccurate. In other words, it can consistently give the same wrong measurement.

Resolution. This is the smallest unit of measure that can be displayed by the measuring device. If a digital caliper displays measurements to four decimal places, then the *resolution* is 0.0001 in (or millimeters).

Devices

Micrometers. Micrometers are used to measure thickness or diameter (Fig. 1.5).

Calipers. Calipers are highly versatile devices used to measure length (Fig. 1.6). They are designed to allow the operator to measure outside dimensions, inside dimensions, and depths. Digital readouts

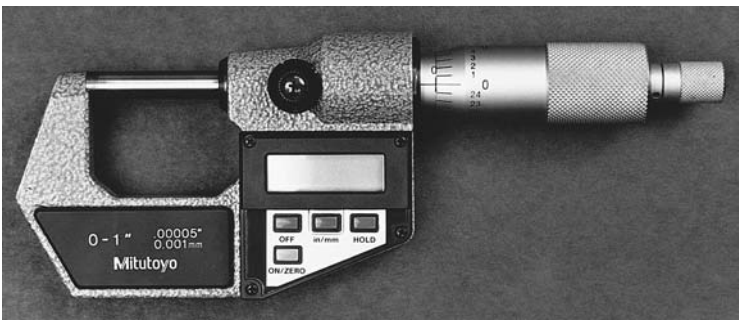

Figure 1.5 Digital micrometer.

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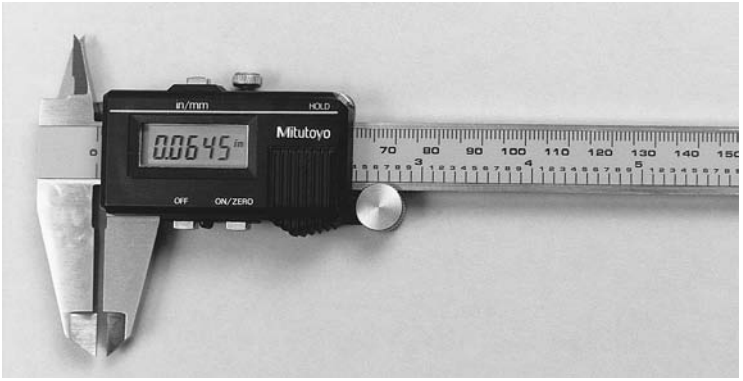

Figure 1.6 Digital caliper.

permit the operator to toggle between millimeters and inches as needed.

Dial indicators. Dial indicators show linear displacement of a stylus as it is moved across the surface of a part or vice versa (Fig. 1.7). They can be used to measure features such as the roundness of a rotational part, the flatness of a surface, or the depth of a hole.

Height gages. Height gauges measure the height of a feature, as the name implies (Fig. 1.8).

1.3 Statistical Process Control

Modern handheld digital measurement devices can be interfaced with computers on the shop floor for use with statistical process control (SPC) programs. Measurements collected from these devices do much more than indicate whether any individual part is within specifications. When the measurements for a succession of parts are plotted graphically, the machine operator can detect any nonrandom trends in machine performance visually and then take corrective action if necessary.

1.3.1 Process capability

When a process planner selects machines to perform a given operation on a part, he or she must know whether or not the machine

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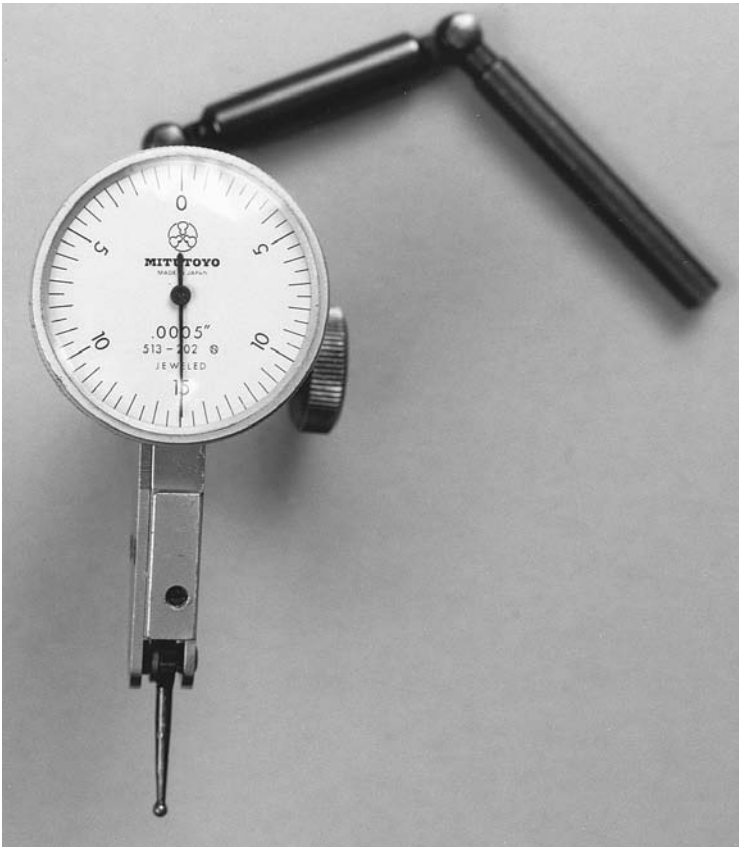

Figure 1.7 Dial indicator.

is capable of satisfying the tolerances specified for that part. The process capability study is used to determine whether or not this is the case. For a given feature, a target dimension is specified along with upper and lower tolerance values. For instance, the specification

$$2.5 \pm \frac{0.003}{0.003}$$

has a target value of 2.500 in, an upper specification limit (USL) of 2.503 in, and a lower specification limit (LSL) of 2.497 in.

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Figure 1.8 Height gauge.

CpK is one measure of process capability that provides an indication of both accuracy and precision:

$$CpK = \min\left\{\frac{USL - \bar{X}}{3\sigma}, \frac{\bar{X} - LSL}{3\sigma}\right\}$$

where σ is usually estimated by *S:*

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$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \bar{X}\right)^2}{n-1}}$$

$$\bar{X} = \frac{\sum_{i=1}^{n} x_i}{n}$$

where USL = upper limit on the tolerance
LSL = lower limit on the tolerance
$\bar{X}$ = process mean, or average value of a set of measurements
σ = standard deviation of entire population of parts
S = standard deviation of measurements from a sampling of n parts

When $CpK \geq 1$, then one can conclude that at least 99.73 percent of the parts produced will fall within the range specified by the LSL and USL. In plain English, this means that the process is centered sufficiently close to the target dimension value and that the spread of measurements is smaller than the tolerance range for that feature. If $CpK < 1$, then one can conclude that fewer than 99.73 percent of the parts produced will meet the design specifications. In this case, the manufacturing engineer can consider alternative processes, or he or she can work to improve the existing process in order to get the defects to an acceptable rate.

Example The width of a slot has a design specification of 2.500 ± 0.003 in. The slot width for each part in a batch of 30 parts has been measured, and the average value of the 30 measurements is 2.501 in. The standard deviation of these 30 measurements is 0.0008.

$$CpK = \min\left\{\frac{2.503 - 2.501}{3(0.0008)}, \frac{2.501 - 2.497}{3(0.0008)}\right\}$$

$$= \min\{0.833, 1.667\}$$

$$= 0.833$$

The CpK value of 0.833 indicates that the defect rate for this process will be unacceptably high if this company is striving for 99.73 percent acceptance rate (i.e., 6σ manufacturing).

1.3.2 Control charts

Variations in the dimensions produced by a process can either be *random* or *assignable*. All metalworking processes inherently produce

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a certain amount of *random variation* in feature sizes that are produced. The magnitude of this random variation is what determines whether or not a machine is capable of meeting required tolerances for a given part. There also may be *assignable variation* present. Assignable variability refers to variations that can be attributed specifically to a particular cause. For example, a metal chip may be lodged beneath parallels supporting a part in a vise. The chip will raise the height of the part, thus increasing the depth of cut beyond what was intended. This is an assignable cause of variation that can be identified and eliminated. Control charts are an extremely valuable tool. They allow the machine operator to see graphically both sudden and gradual shifts in the process.

Many different types of control charts are available, and interested readers are encouraged to consult books dedicated to statistical process control. In its simplest form, a process control chart graphically plots the measured dimensions for the last 20 parts (typically) to be measured. The target value, USL, and LSL are also indicated on the chart. Much more sophisticated SPC tools are available, but even this simple control chart allows a machine operator to detect either sudden or gradual shifts in process performance. For example, Fig. 1.9 shows measurements of a feature for 20 parts. The nominal (target) measurement is 2.500 in, with an allowable tolerance of ±0.003 in. This chart clearly shows an upward nonrandom trend in the size of this feature. On seeing a nonrandom (i.e.,

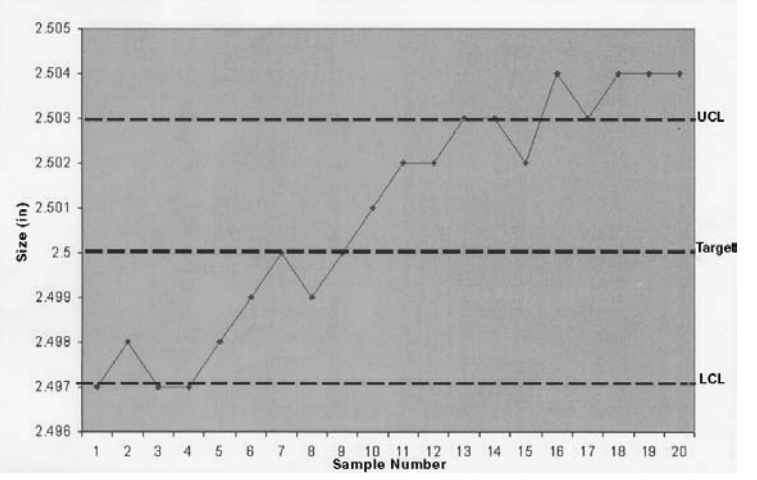

Figure 1.9 Control chart indicating upward trend.

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assignable) cause of variation, the machine operator would know that he or she should stop the machine and investigate the root cause of this variation before parts are produced outside specifications. The root cause could be a cutting tool that is shifting in its collett or any number of other problems.

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Chapter

2

Mathematics for Machinists and Metalworkers

This chapter covers all the basic and special mathematical procedures of value to the modern machinist and metalworker. Geometry and plane trigonometry are of prime importance, as are the basic algebraic manipulations. Solutions to many basic and complex machining and metalworking operations would be difficult or impossible without the use of these branches of mathematics. In this chapter and other subsections of this *Handbook*, all the basic and important aspects of these branches of mathematics will be covered in detail.

2.1 General Mathematics, Algebra, and Trigonometry

2.1.1 General mathematics and algebraic procedures

If $A/B = C/D$, then

$$A = \frac{BC}{D} \quad B = \frac{AD}{C} \quad C = \frac{AD}{B} \quad \text{and} \quad D = \frac{BC}{A}$$

Transposing an equation. We may solve for any one unknown if all other variables are known. The given equation is

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$$R = \frac{Gd^4}{8ND^3}$$

an equation with five variables, shown in terms of R. Solving for G gives

$$Gd^4 = R8ND^3 \text{ (cross-multiplied)}$$
$$G = \frac{8RND^3}{d^4}$$

Solving for d gives

$$d = \sqrt[4]{\frac{8RND^3}{G}}$$

Solving for D gives

$$D = \sqrt[3]{\frac{GD^4}{8RN}}$$

Solve for N using the same transposition procedures just shown.

Solving a typical algebraic equation. An algebraic equation can be solved by substituting the numerical values assigned to the variables, which are denoted by letters, and then finding the unknown value.

Example:

$$L = 2C + 1.57(D + d) + \frac{(D - d)^2}{4C} \qquad \text{(belt-length equation)}$$

If $C = 16$, $D = 5.56$, and $d = 3.12$ (the variables), solve for L (by substituting the values of the variables into the equation):

$$L = 2(16) + 1.57(5.56 + 3.12) + \frac{(5.56 - 3.12)^2}{4(16)} = 45.721$$

Most of the equations shown in this *Handbook* are solved in a similar manner, i.e., by substituting known values for the variables in the equations and solving for the unknown quantity using standard algebraic and trigonometric rules and procedures.

Ratios and proportions. If $a/b = c/d$, then

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$$\frac{a+b}{b}=\frac{c+d}{d} \quad \text{and} \quad \frac{a-b}{b}=\frac{c-d}{d} \quad \text{and} \quad \frac{a-b}{a+b}=\frac{c-d}{c+d}$$

Quadratic equations. Any quadratic equation may be reduced to the form

$$ax^2 + bx + c = 0$$

The two roots, x_1 and x_2, equal

$$\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

When a, b, and c are real, if $b^2 - 4ac$ is positive, the roots are real and unequal. If $b^2 - 4ac$ is zero, the roots are real and equal. If $b^2 - 4ac$ is negative, the roots are imaginary and unequal.

2.1.2 Plane trigonometry

There are six trigonometric functions: sine, cosine, tangent, cotangent, secant, and cosecant. The relationship of the trigonometric functions is shown in Fig. 2.1. Trigonometric functions shown for angle A (right-angled triangle) include

$$\sin A = a/c \text{ (sine)}$$

$$\cos A = b/c \text{ (cosine)}$$

$$\tan A = a/b \text{ (tangent)}$$

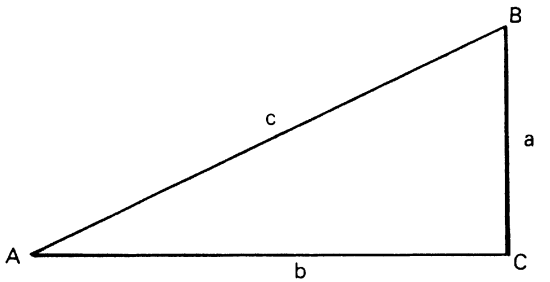

Figure 2.1 Right-angled triangle.

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$$\cot A = b/a \text{ (cotangent)}$$

$$\sec A = c/b \text{ (secant)}$$

$$\csc A = c/a \text{ (cosecant)}$$

For angle B, the functions would become

$$\sin B = b/c \text{ (sine)}$$

$$\cos B = a/c \text{ (cosine)}$$

$$\tan B = b/a \text{ (tangent)}$$

$$\cot B = a/b \text{ (cotangent)}$$

$$\sec B = c/a \text{ (secant)}$$

$$\csc B = c/b \text{ (cosecant)}$$

As can be seen from the preceding, the sine of a given angle is always the side opposite the given angle divided by the hypotenuse of the triangle, the cosine is always the side adjacent to the given angle divided by the hypotenuse, and the tangent is always the side opposite the given angle divided by the side adjacent to the angle. These relationships must be remembered at all times when performing trigonometric operations. Also,

$$\sin A = 1/\csc A$$

$$\cos A = 1/\sec A$$

$$\tan A = 1/\cot A$$

This reflects the important fact that the cosecant, secant, and cotangent are the reciprocals of the sine, cosine, and tangent, respectively. This fact also must be remembered when performing trigonometric operations.

Also, in any right-angled triangle,

$$\sin x = \cos (90^\circ - x)$$

$$\cos x = \sin (90^\circ - x) \qquad (x \text{ is the given angle other than } 90^\circ)$$

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$$\tan x = \cot (90° - x)$$

Equivalent expressions. The following trigonometric expressions are mathematically equivalent and may be used to advantage in solving many trigonometric problems. It is wise to try to remember as many of these expressions as possible, although they may be referred to in this chapter of the *Handbook* as required.

$$\tan x = \frac{\sin x}{\cos x}$$

$$\cot x = \frac{\cos x}{\sin x}$$

$$\sin^2 x + \cos^2 x = 1$$

$$\sin x = \pm\sqrt{1 - \cos^2 x}$$

$$\cos x = \pm\sqrt{1 - \sin^2 x}$$

$$\tan x = \pm\sqrt{\sec^2 x - 1}$$

$$\cot x = \pm\sqrt{\csc^2 x - 1}$$

$$\sec x = \pm\sqrt{\tan^2 x + 1}$$

$$\csc x = \pm\sqrt{\cot^2 x + 1}$$

Note: The choice of the ± sign is determined by which quadrant the angle x is situated in (see "Signs and Limits of Trigonometric Functions" below).

Signs and limits of the trigonometric functions. The following coordinate chart shows the sign of the function in each quadrant and its numerical limits. As an example, the sine of any angle between 0 and 90° will always be positive, and its numerical value will range between 0 and 1, whereas the cosine of any angle between 90 and 180° will always be negative, and its numerical value will range between 0 and 1. Each quadrant contains 90°; thus the fourth quadrant ranges between 270 and 360°.

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Quadrant II	y	**Quadrant I**
(1–0) + sin		sin + (0–1)
(0–1) − cos		cos + (1–0)
(∞–0) − tan		tan + (0–∞)
(0–∞) − cot		cot + (∞–0)
(∞–1) − sec		sec + (1–∞)
(1–∞) + csc		csc + (∞–1)
x'		x
Quadrant III	0	**Quadrant IV**
(0–1) − sin		sin − (1–0)
(1–0) − cos		cos + (0–1)
(0–∞) + tan		tan − (∞–0)
(∞–0) + cot		cot − (0–?)
(1–∞) − sec		sec + (∞–1)
(∞–1) − csc	y'	csc − (1–∞)

Trigonometric laws. The trigonometric "laws" show the relationships between the sides and angles of non-right-angle triangles or acute and obtuse triangles and allow us to calculate the unknown parts of the triangle when certain values are known. Refer to Fig. 2.2 for illustrations of the trigonometric laws that follow.

The law of sines (see Fig. 2.2)

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$

$$\frac{a}{b} = \frac{\sin A}{\sin B} \qquad \frac{b}{c} = \frac{\sin B}{\sin C} \qquad \frac{a}{c} = \frac{\sin A}{\sin C}$$

The law of cosines (see Fig. 2.2)

$$a^2 = b^2 + c^2 - 2bc \cos A$$

$$b^2 = a^2 + c^2 - 2ac \cos B$$

$$c^2 = a^2 + b^2 - 2ab \cos C$$

The law of tangents (see Fig. 2.2)

$$\frac{a+b}{a-b} = \frac{\tan \dfrac{A+B}{2}}{\tan \dfrac{A-B}{2}}$$

With the preceding laws, the trigonometric functions for right-angled triangles, the Pythagorean theorem, and the following triangle

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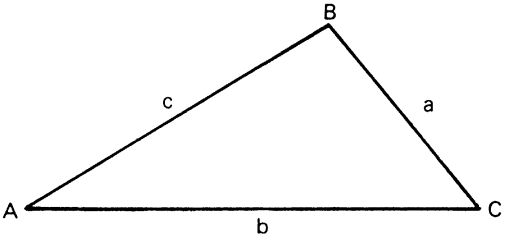

Figure 2.2 Oblique triangle.

solution chart, it will be possible to find the solution to any plane triangle problem, provided the correct parts are specified.

The Solution of Triangles

In right-angled triangles	To solve
Known: Any two sides	Use the Pythagorean theorem to solve unknown side; then use the trigonometric functions to solve the two unknown angles. The third angle is 90°.
Known: Any one side and either angle that is not 90°	Use trigonometric functions to solve the two unknown sides. The third angle is 180°—the sum of two known angles.
Known: Three angles and no sides *(all* triangles)	Cannot be solved because there are an infinite number of triangles that satisfy three known internal angles.
Known: Three sides	Use trigonometric functions to solve the two unknown angles.
In oblique triangles	**To solve**
Known: Two sides and any one of two nonincluded angles	Use the law of sines to solve the second unknown angle. The third angle is 180°—the sum of two known angles. Then find the other sides using the law of sines or the law of tangents.
Known: Two sides and the included angle	Use the law of cosines for one side and the law of sines for the two angles.
Known: Two angles and any one side	Use the law of sines to solve the other sides or the law of tangents. The third angle is 180°—the sum of two known angles.
Known: Three sides	Use the law of cosines to solve two of the unknown angles. The third angle is 180°—the sum of two known angles.

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The Solution of Triangles (*Continued*)

In oblique triangles	To solve
Known: One angle and one side (non-right triangle)	Cannot be solved except under certain conditions. If the triangle is equilateral or isosceles, it may be solved if the known angle is opposite the known side.

Finding heights of non-right-angled triangles. The height x shown in Fig. 2.3 and Fig. 2.4 is found from

$$x = b\frac{\sin A \sin C}{\sin(A+C)} = \frac{b}{\cot A + \cot C} \qquad \text{(for Fig. 2.3)}$$

$$x = b\frac{\sin A \sin C}{\sin(C'-A)} = \frac{b}{\cot A - \cot C'} \qquad \text{(for Fig. 2.4)}$$

Areas of triangles (see Fig. 2.5)

$$A = \tfrac{1}{2}bh$$

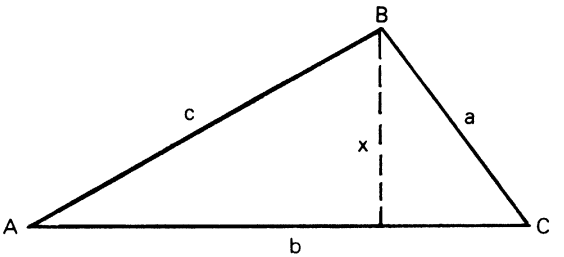

Figure 2.3 Height of triangle x.

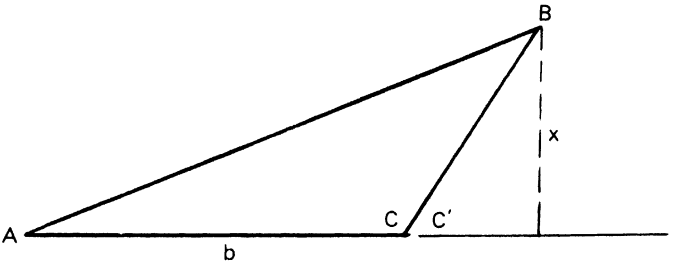

Figure 2.4 Height of triangle x.

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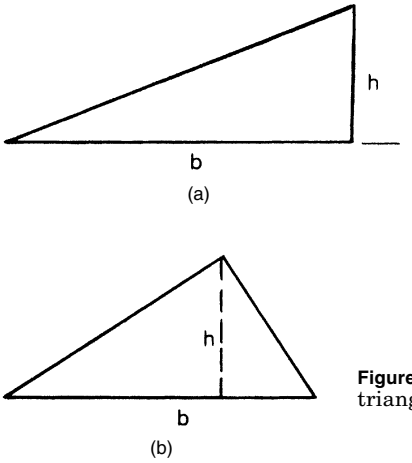

Figure 2.5 Triangles: (*a*) right triangle, (*b*) oblique triangle.

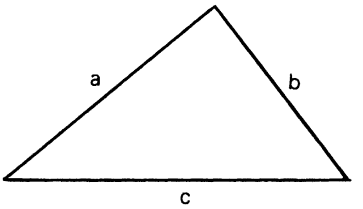

Figure 2.6 Triangle.

The area when the three sides are known is (see Fig. 2.6) (this holds true for any triangle)

$$A = \sqrt{s(s-a)(s-b)(s-c)}$$

where $s = \dfrac{a+b+c}{2}$

The Pythagorean theorem (for right-angled triangles)

$$c^2 = a^2 + b^2$$

$$b^2 = c^2 - a^2$$

$$a^2 = c^2 - b^2$$

Note: Side c is the hypotenuse.

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Converting angles to decimal degrees. Angles given in degrees, minutes, and seconds must be converted to decimal degrees prior to finding the trigonometric functions of the angle on a handheld calculator.

Procedure: Convert 26°41′26″ to decimal degrees.

Degrees =	26.000000	in decimal degrees
Minutes = 41/60	= 0.683333	in decimal parts of a degree
Seconds = 26/3600	= 0.007222	in decimal parts of a degree

The angle in decimal degrees is then

$$26.000000 + 0.683333 + 0.007222 = 26.690555°$$

Converting decimal degrees to degrees, minutes, and seconds

Procedure: Convert 56.5675 decimal degrees to degrees, minutes, and seconds.

$$\text{Degrees} = 56 \text{ degrees}$$

$$\text{Minutes} = 0.5675 \times 60 = 34.05 = 34 \text{ minutes}$$

$$\text{Seconds} = 0.05 \text{ (minutes)} \times 60 = 3 \text{ seconds}$$

The answer, therefore, is 56°34′3″.

Samples of solutions to triangles

Solving right-angled triangles by trigonometry. Required: Any one side and angle A or angle B (see Fig. 2.7). Solve for side a:

$$\sin A = \frac{a}{c}$$

$$\sin 33.162° = \frac{a}{3.625}$$

$$a = 1.9829$$

Solve for side b:

$$\cos A = \frac{b}{c}$$

$$\cos 33.162° = \frac{b}{3.625}$$

$$b = 3.0345$$

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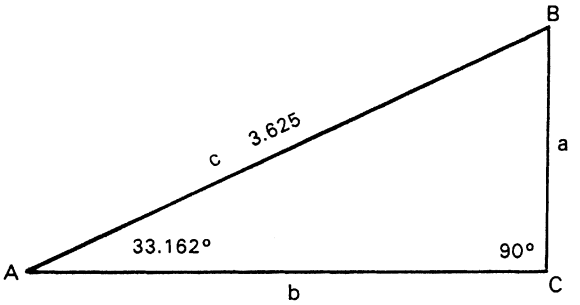

Figure 2.7 Solve the triangle.

Then angle $B = 180° - (\text{angle } A + 90°) = 180° - 123.162° = 56.838°$. We now know sides a, b, and c and angles A, B, and C.

Solving non-right-angled triangles using the trigonometric laws. Solve the triangle in Fig. 2.8 given two angles and one side:

$$A = 45°$$

$$B = 109°$$

$$a = 3.250$$

First, find angle C:

$$\begin{aligned} \text{Angle } C &= 180° - (\text{angle } A + \text{angle } B) \\ &= 180° - (45° + 109°) \\ &= 180° - 154° \\ &= 26° \end{aligned}$$

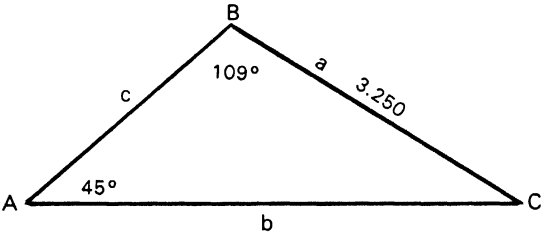

Figure 2.8 Solve the triangle.

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Second, find side b by the law of sines:

$$\frac{a}{\sin A} = \frac{b}{\sin B}$$

$$\frac{3.250}{0.07071} = \frac{b}{0.9455}$$

$$b = 4.3457$$

Third, find side c by the law of sines:

$$\frac{a}{\sin A} = \frac{c}{\sin C}$$

$$\frac{3.250}{0.07071} = \frac{c}{0.4384}$$

$$c = 2.0150$$

Solve the triangle in Fig. 2.9 given two sides and one angle:

$$\text{Angle } A = 16°$$

$$a = 1.562$$

$$b = 2.509$$

First, find angle B from the law of sines:

$$\frac{a}{\sin A} = \frac{b}{\sin B}$$

$$\frac{1.562}{\sin 16} = \frac{2.509}{B}$$

$$B = 26.276°$$

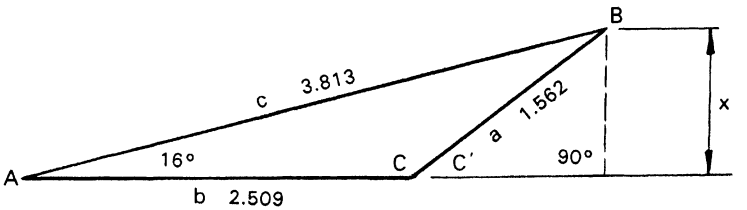

Figure 2.9 Solve the triangle.

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Second, find angle C:

$$\text{Angle } C = 180^\circ - (\text{angle } A + \text{angle } B)$$

$$= 180^\circ - 42.276^\circ$$

$$= 137.724^\circ$$

Third, find side c from the law of sines:

$$\frac{a}{\sin A} = \frac{c}{\sin C}$$

$$\frac{1.562}{0.2756} = \frac{c}{0.6727}$$

$$c = 3.813$$

We may now find the altitude or height x of this triangle (see Fig. 2.9). Refer to Fig. 2.4.

$$x = b\frac{\sin A \sin C}{\sin(C' - A)} \qquad \text{(where angle C}' = 180^\circ - 137.724^\circ = 42.276^\circ\text{)}$$

$$= 2.509 \times \frac{0.2756 \times 0.6727}{\sin(42.276 - 16)}$$

$$= 1.051$$

This height x also can be found from the sine function of angle C' when side a is known, as shown below:

$$\sin C' = \frac{x}{1.562}$$

$$x = 1.562 \sin C' = 1.562 \times 0.6727 = 1.051$$

Both methods yield the same numerical solution of 1.051.

Solve the triangle in Fig. 2.9a given three sides and no angles. According to the preceding triangle solution chart, solving this triangle requires use of the law of cosines. Proceed as follows: First, solve for any angle (we will take angle C first):

$$c^2 = a^2 + b^2 - 2ab \cos C$$

$$(1.75)^2 = (1.1875)^2 + (2.4375)^2 - 2(1.1875 \times 2.4375) \cos C$$

$$\cos C = 0.7409$$

$$\text{arc cos } C = 42.192^\circ$$

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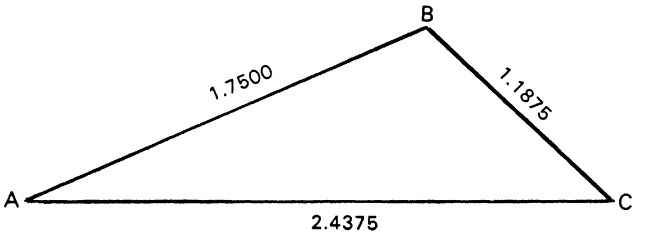

Figure 2.9a Solve the triangle.

Second, by the law of cosines, find angle B:

$$b^2 = a^2 + c^2 - 2ac \cos B$$

$$(2.4375)^2 = (1.1875)^2 + (1.7500)^2 - 2(1.1875 \times 1.7500) \cos B$$

$$\cos B = -0.3534$$

$$\text{arc cos } B = 110.695°$$

Then angle A is found from

$$\text{Angle } A = 180 - (42.192 + 110.695)$$

$$= 27.113°$$

Converting degrees to radians. To convert from degrees to radians, you must first find the degrees as decimal degrees. If R represents radians, then

$$2\pi R = 360° \qquad \text{or} \qquad \pi R = 180°$$

From this,

$$1 \text{ radian} = 57.2957795°$$

and

$$1° = 0.0174533 \text{ radian}$$

Example: Convert 56.785° to radians.

$$56.785° \times 0.0174533 = 0.9911 \text{ radian}$$

Example: Convert $2.0978R$ to decimal degrees.

$$57.2957795 \times 2.0978 = 120.0591°$$

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2.1.3 Important mathematical constants

$$\pi = 3.1415926535898$$

$$1 \text{ radian} = 57.295779513082^\circ$$

$$1^\circ = 0.0174532925199 \text{ radian}$$

$$2\pi R = 360^\circ$$

$$\pi R = 180^\circ$$

$$e = 2.718281828 \text{ (base of natural logarithms)}$$

2.1.4 Summary of trigonometric procedures for triangles

There are four possible cases in the solution of oblique triangles:

Case 1: Given one side and two angles: *a, A, B*

Case 2: Given two sides and the angle opposite them: *a, b, A* or *B*

Case 3: Given two sides and their included angle: *a, b, C*

Case 4: Given the three sides: *a, b, c*

All oblique (non-right-angle) triangles can be solved by use of natural trigonometric functions: the law of sines, the law of cosines, and the angle formula: angle A + angle B + angle $C = 180^\circ$. This may be done in the following manner:

Case 1: Given *a, A,* and *B,* angle *C* may be found from the angle formula, and then sides *b* and *c* may be found by using the law of sines twice.

Case 2: Given *a, b,* and *A,* angle *B* may be found by the law of sines, angle *C* from the angle formula, and side *c* by the law of sines again.

Case 3: Given *a, b,* and *C*, side *c* may be found by the law of cosines, and angles *A* and *B* may be found by the law of sines used twice or angle *A* from the law of sines and angle *B* from the angle formula.

Case 4: Given *a, b,* and *c*, the angles all may be found by the law of cosines, or angle *A* may be found from the law of cosines, and angles *B* and *C* from the law of sines, or angle *A* from the law of cosines, angle *B* from the law of sines, and angle *C* from the angle formula.

Note: Case 2 is called the *ambiguous case,* in which there may be one solution, two solutions, or *no* solution, given *a, b,* and *A*.

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- If angle $A < 90°$ and $a < b \sin A$, there is *no* solution.
- If angle $A < 90°$ and $a = b \sin A$, there is one solution—a right triangle.
- If angle $A < 90°$ and $b > a > b \sin A$, there are two solutions—oblique triangles.
- If angle $A < 90°$ and $a \geq b$, there is one solution—an oblique triangle.
- If angle $A < 90°$ and $a \leq b$, there is *no* solution.
- If angle $A > 90°$ and $a > b$, there is one solution—an oblique triangle.

Special half-angle formulas. In case 4 triangles where only the three sides *a, b,* and c are known, the sets of half-angle formulas shown below may be used to find the angles:

$$\sin\frac{A}{2} = \sqrt{\frac{(s-b)(s-c)}{bc}}$$

$$\sin\frac{B}{2} = \sqrt{\frac{(s-c)(s-a)}{ca}}$$

$$\sin\frac{C}{2} = \sqrt{\frac{(s-a)(s-b)}{ab}}$$

$$\cos\frac{A}{2} = \sqrt{\frac{s(s-a)}{bc}}$$

$$\cos\frac{B}{2} = \sqrt{\frac{s(s-b)}{ac}}$$

$$\cos\frac{C}{2} = \sqrt{\frac{s(s-c)}{ab}}$$

$$\tan\frac{A}{2} = \sqrt{\frac{(s-b)(s-c)}{s(s-a)}}$$

$$\tan\frac{B}{2} = \sqrt{\frac{(s-c)(s-a)}{s(s-b)}}$$

$$\tan\frac{C}{2} = \sqrt{\frac{(s-a)(s-b)}{s(s-c)}}$$

where $s = \sqrt{\frac{a+b+c}{2}}$

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2.1.5 Powers-of-10 notation

Numbers written in the form 1.875×10^5 or 3.452×10^{-6} are so stated in powers-of-10 notation. Arithmetic operations on numbers that are either very large or very small are processed easily and conveniently using the powers-of-10 notation and procedures. If you will note, on the handheld scientific calculator this process is carried out automatically by the calculator. If the calculated answer is larger or smaller than the digital display can handle, the answer will be given in powers-of-10 notation.

This method of handling numbers is always used in scientific and engineering calculations when the values of the numbers so dictate. Engineering notation usually is given in multiples of 3, such as 1.246×10^3, 6.983×10^{-6}, etc.

How to calculate with powers-of-10 notation. Numbers with many digits may be expressed more conveniently in powers-of-10 notation, as shown below:

$$0.000001389 = 1.389 \times 10^{-6}$$

$$3{,}768{,}145 = 3.768145 \times 10^6$$

You are actually counting the number of places that the decimal point is shifted, either to the right or to the left. Shifting to the right produces a negative exponent, and shifting to the left produces a positive exponent.

Multiplication, division, exponents, and radicals in powers-of-10 notation are handled easily, as shown below:

$$(1.246 \times 10^4) \times (2.573 \times 10^{-4}) = 3.206 \times 10^0 = 3.206 \quad (\textbf{Note: } 10^0 = 1)$$

$$(1.785 \times 10^7) \div (1.039 \times 10^{-4}) = (1.785/1.039) \times 10^{7-(-4)} = 1.718 \times 10^{11}$$

$$(1.447 \times 10^5)^2 = (1.447)^2 \times 10^{10} = 2.094 \times 10^{10}$$

$$\sqrt{1.391 \times 10^8} = 1.391^{1/2} \times 10^{8/2} = 1.179 \times 10^4$$

In the preceding examples, you must use the standard algebraic rules for addition, subtraction, multiplication, and division of exponents or powers of numbers. Thus

- Exponents are algebraically added for multiplication.
- Exponents are algebraically subtracted for division.
- Exponents are algebraically multiplied for power raising.
- Exponents are algebraically divided for taking roots.

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2.2 Geometric Principles

In any triangle, angle A + angle B + angle C = 180°, and angle A = 180° − (angle A + angle B), and so on (see Fig. 2.10). If three sides of one triangle are proportional to the corresponding sides of another triangle, the triangles are similar. Also, if $a{:}b{:}c = a'{:}b'{:}c'$, then angle A = angle A', angle B = angle B', angle C = angle C', and $a/a' = b/b' = c/c'$. Conversely, if the angles of one triangle are equal to the respective angles of another triangle, the triangles are similar and their sides proportional; thus, if angle A = angle A', angle B = angle B', and angle C = angle C', then $a{:}b{:}c = a'{:}b'{:}c'$ and $a/a' = b/b' = c/c'$ (see Fig. 2.11).

- *Isosceles triangle* (see Fig. 2.12). If side c = side b, then angle A = angle B.

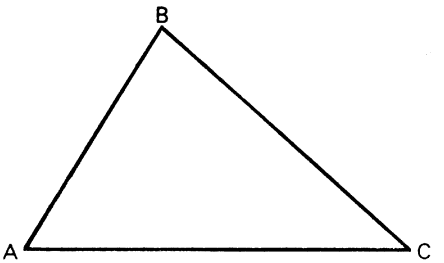

Figure 2.10 Triangle.

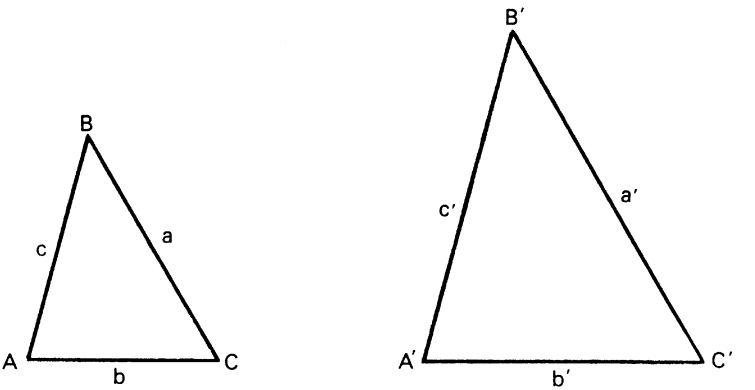

Figure 2.11 Similar triangles.

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- *Equilateral triangle* (see Fig. 2.13). If side a = side b = side c, angles A, B, and C are equal (60°)
- *Right triangle* (see Fig. 2.14). $c^2 = a^2 + b^2$ and $c = (a^2 + b^2)^{1/2}$ when angle $C = 90°$. Therefore, $a = (c^2 - b^2)^{1/2}$ and b $= (c^2 - a^2)^{1/2}$. This relationship in all right angle triangles is called the Pythagorean theorem.
- *Exterior angle of a triangle* (see Fig. 2.15). Angle C = angle A + angle B.
- *Intersecting straight lines* (see Fig. 2.16). Angle A = angle A', and angle B = angle B'.

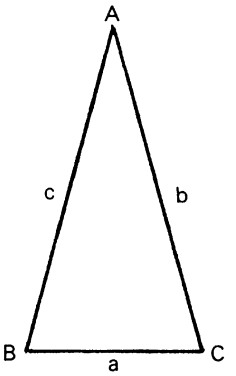

Figure 2.12 Isosceles triangle.

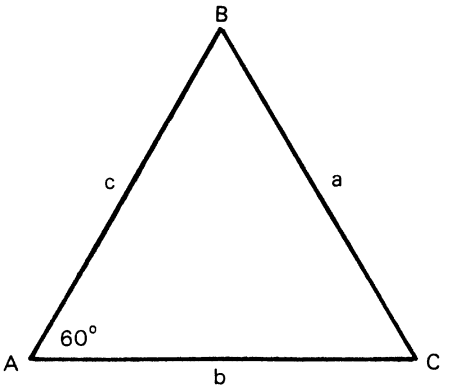

Figure 2.13 Equilateral triangle.

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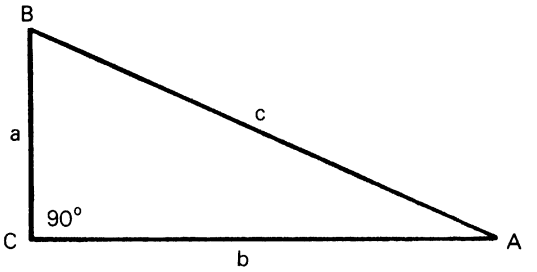

Figure 2.14 Right-angled triangle.

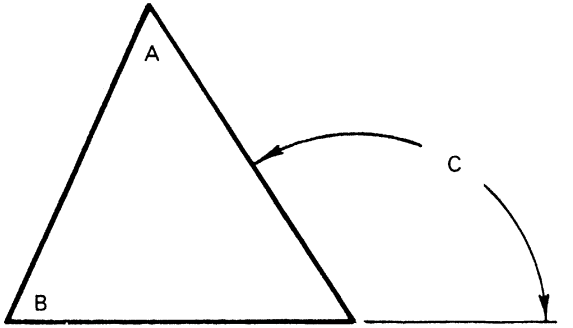

Figure 2.15 Exterior angle of a triangle.

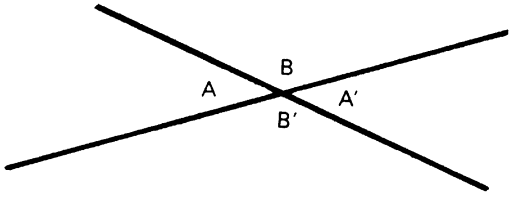

Figure 2.16 Intersecting straight lines.

- *Two parallel lines intersected by a straight line* (see Fig. 2.17). Alternate interior and exterior angles are equal: Angle A = angle A', and angle B = angle B'.
- *Any four-sided geometric figure* (see Fig. 2.18). The sum of all interior angles = 360°; angle A + angle B + angle C + angle D = 360°.
- *A line tangent to a point on a circle is at 90°, or normal, to a radial line drawn to the tangent point* (see Fig. 2.19).

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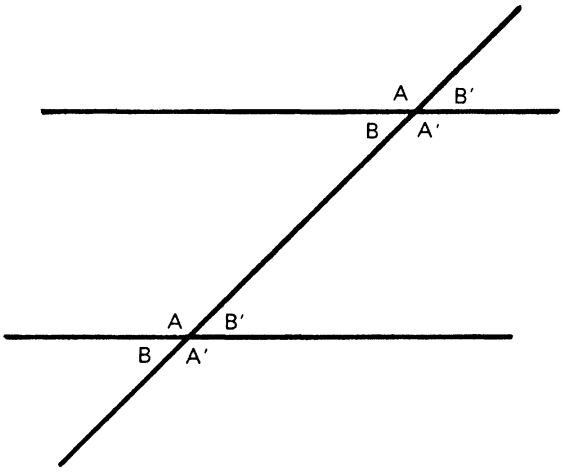

Figure 2.17 Straight line intersecting two parallel lines.

Figure 2.18 Quadrilateral (four-sided figure).

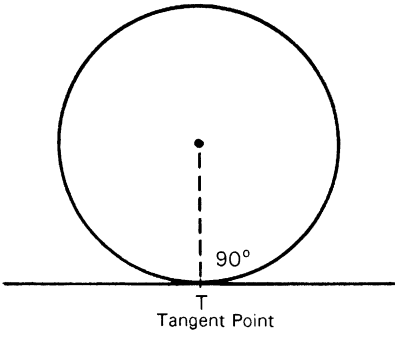

Figure 2.19 Tangent at a point on a circle.

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- *Two circles' common point of tangency is intersected by a line drawn between their centers* (see Fig. 2.20).
  Side $a = a'$; angle A = angle A' (see Fig. 2.21).
  Angle A = ½ angle B (see Fig. 2.22).
  Angle A = angle B = angle C. All perimeter angles of a chord are equal (see Fig. 2.23).
  Angle B = ½ angle A (see Fig. 2.24).
  $a^2 = bc$ (see Fig. 2.25).

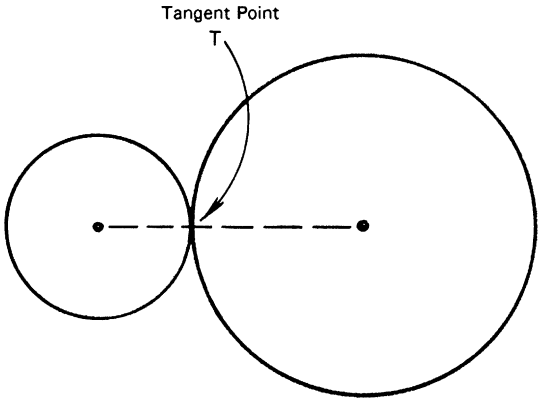

Figure 2.20 Common point of tangency.

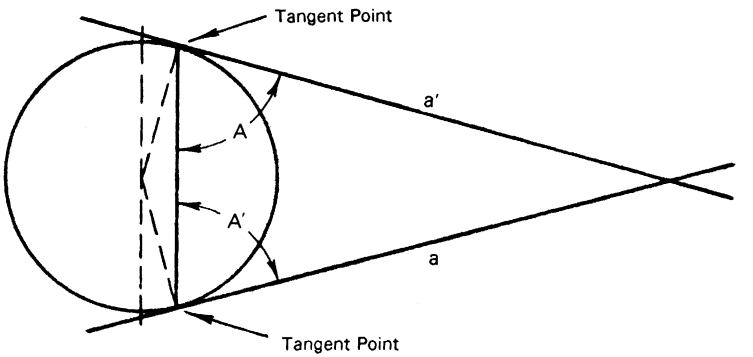

Figure 2.21 Tangents and angles.

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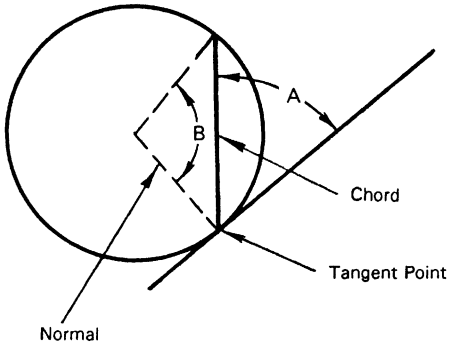

Figure 2.22 Half-angle (A)

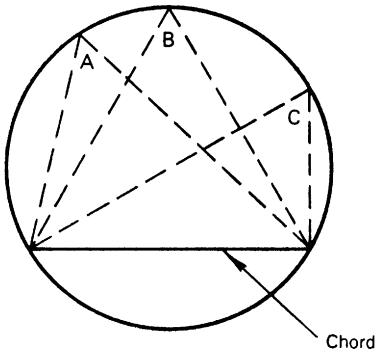

Figure 2.23 Perimeter angles of a chord.

- *All perimeter angles in a circle, drawn from the diameter, are 90°* (see Fig. 2.26).
- *Arcs are proportional to internal angles* (see Fig. 2.27). Angle A : angle $B = a{:}b$. Thus, if angle $A = 89°$, angle $B = 30°$, and arc $a = 2.15$ minutes, arc b would be calculated as

$$\frac{\text{Angle } A}{\text{Angle } B} = \frac{a}{b}$$

$$\frac{89}{30} = \frac{2.15}{b}$$

$$b = 64.5 = 0.7247\,\text{min}$$

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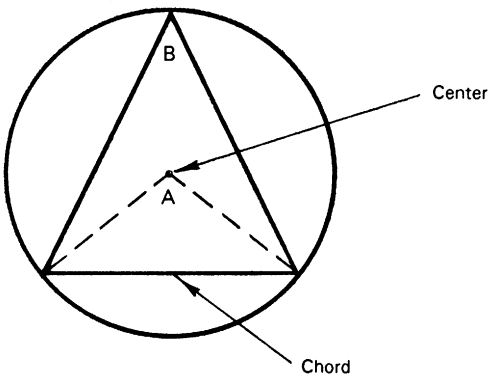

Figure 2.24 Half-angle (B).

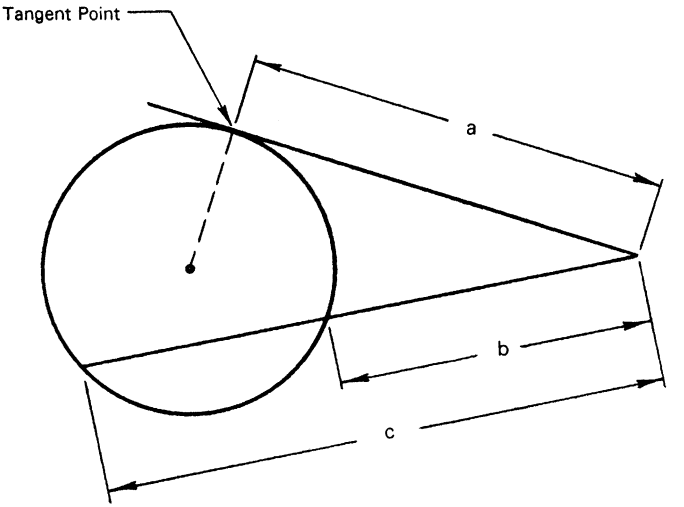

Figure 2.25 Line and circle relationship ($a^2 = bc$).

Note: The angles may be given in decimal degrees or radians, consistently.

- *Circumferences are proportional to their respective radii* (see Fig. 2.28). $C : C' = r : R$, and areas are proportional to the squares of the respective radii.

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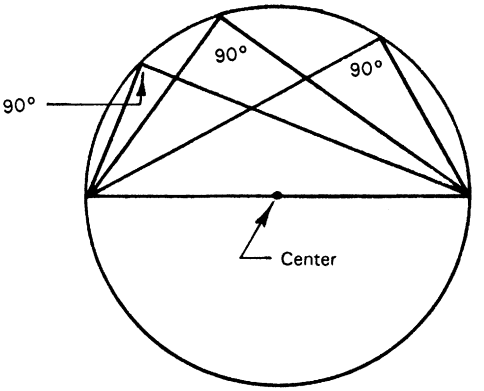

Figure 2.26 Ninety-degree perimeter angles.

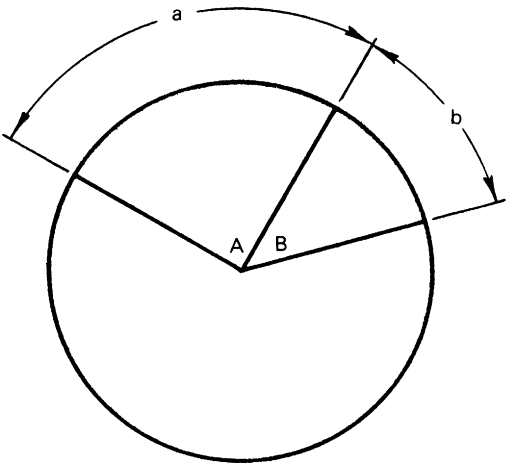

Figure 2.27 Proportional arcs and angles.

2.3 Geometric Construction

The following figures show the methods used to perform most of the basic geometric constructions used in standard drawing practices. Many of these constructions have widespread use in the machine shop and sheet metal shop.

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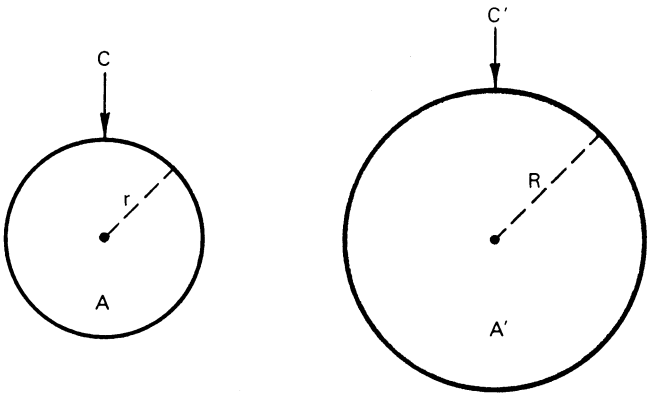

Figure 2.28 Circumference and radii proportionality.

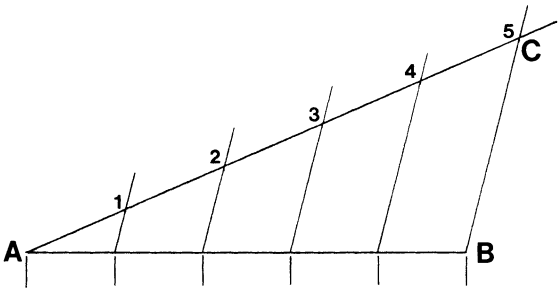

Figure 2.29 Dividing a line equally.

- *To divide any straight line into any number of equal spaces* (Fig. 2.29). To divide line *AB* into five equal spaces, draw line *AC* at any convenient angle such as angle *BAC*. With a divider or compass, mark off five equal spaces along line *AC*. Now connect point 5 on line *AC* with the endpoint of line *AB*. Draw line *CB,* and parallel transfer the other points along line *AC* to intersect line *AB,* thus dividing it into five equal spaces.
- *To bisect any angle BAC* (Fig. 2.30), swing an arc from point *A* through points *d* and *e*. Swing an arc from point *d* and another equal arc from point *e*. The intersection of these two arcs will be at point *f*. Draw a line from point *A* to point *f,* forming the bisector line *AD*.

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- *To divide any line into two equal parts and erect a perpendicular* (Fig. 2.31), draw an arc from point *A* that is more than half the length of line *AB*. Using the same arc length, draw another arc from point *B*. The intersection points of the two arcs meet at points *c* and *d*. Draw the perpendicular bisector line *cd*.
- *To erect a perpendicular line through any point along a line* (Fig. 2.32), from point *c* along line *AB*, mark points 1 and 2 equidistant from point *c*. Select an arc length on the compass greater than the distance from points 1 to *c* or points 2 to *c*. Swing this arc from point 1 and point 2. The intersection of the arcs is at point *f*. Draw a line from point *f* to point *c*, which is perpendicular to line *AB*.

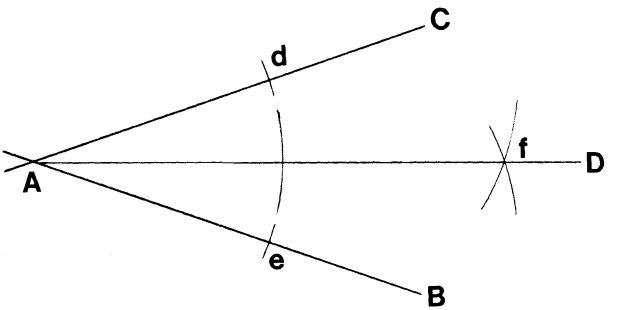

Figure 2.30 Bisecting an angle.

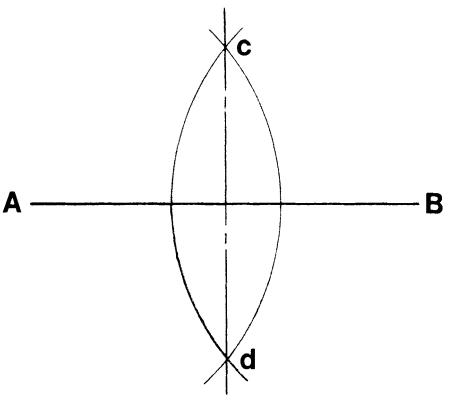

Figure 2.31 Erecting a perpendicular.

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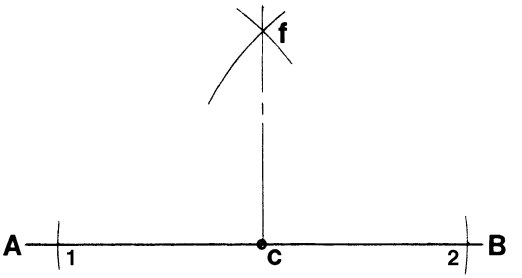

Figure 2.32 Perpendicular to a point.

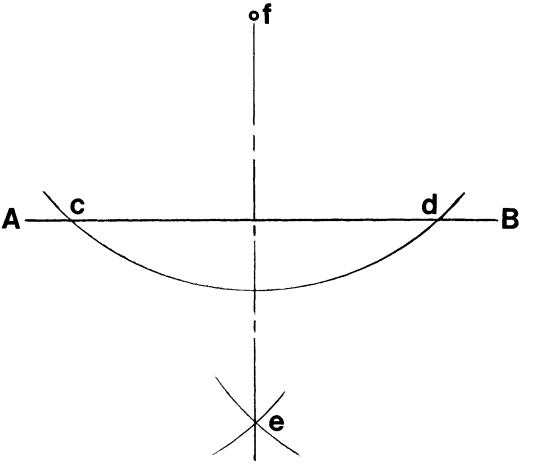

Figure 2.33 Drawing a perpendicular to a line.

- *To draw a perpendicular to a line AB from a point f, a distance from it* (Fig. 2.33), with point *f* as a center, draw a circular arc intersecting line *AB* at points *c* and *d*. With points *c* and *d* as centers, draw circular arcs with radii longer than half the distance between points *c* and *d*. These arcs intersect at point *e*, and line *fe* is the required perpendicular.
- *To draw a circular arc with a given radius through two given points* (Fig. 2.34), with points *A* and *B* as centers and the set given radius, draw circular arcs intersecting at point *f*. With point *f* as a center, draw the circular arc that will intersect both points *A* and *B*.

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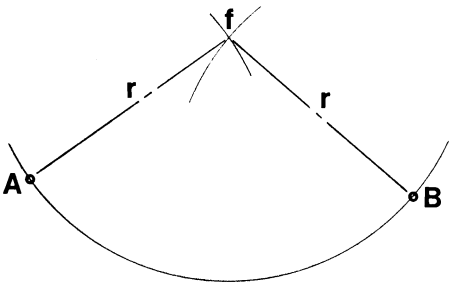

Figure 2.34 Drawing a circular arc through given points.

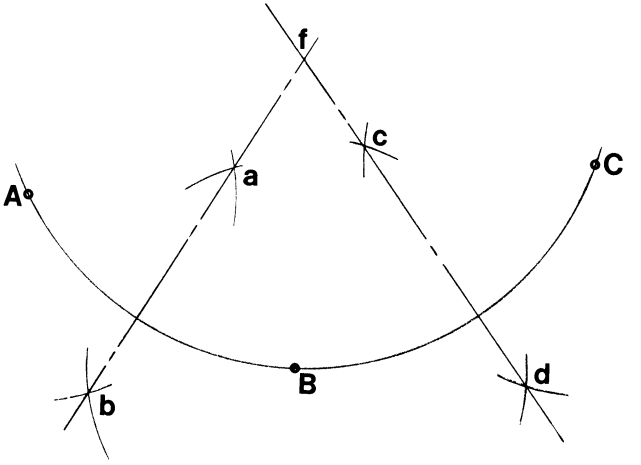

Figure 2.35 Finding the center of a circle.

- *To find the center of a circle or the arc of a circle* (Fig. 2.35), select three points on the perimeter of the given circle such as *A, B,* and *C*. With each of these points as a center and the same radius, describe arcs that intersect each other. Through the points of intersection, draw lines *fb* and *fd*. The intersection point of these two lines is the center of the circle or circular arc.
- *To draw a tangent to a circle from any given point on the circumference* (Fig. 2.36), through the tangent point *f,* draw a radial line *OA*. At point *f,* draw a line *CD* at right angles to *OA*. Line *CD* is the required tangent to point *f* on the circle.

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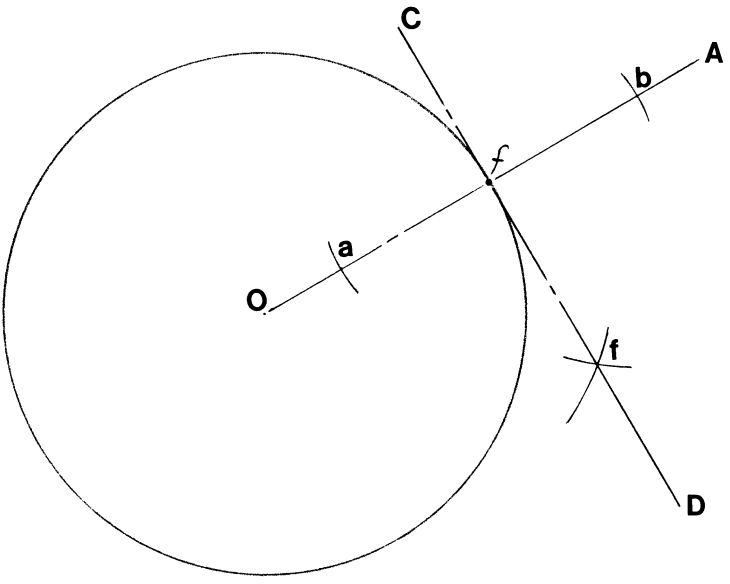

Figure 2.36 Drawing a tangent to a given point on a circle.

- *To draw an ellipse given the major and minor axes using the concentric circle method* (Fig. 2.37), on the two principal diameters *ef* and *cd* that intersect at point *O*, draw circles. From a number of points on the outer circle, such as *g* and *h,* draw radii *Og* and *Oh* intersecting the inner circle at points *g′* and *h′.* From *g* and *h,* draw lines parallel to *Oa,* and from *g′* and *h′,* draw lines parallel to *Od.* The intersection of the lines through *g* and *g′* and *h* and *h′* describe points on the ellipse. Each quadrant of the concentric circles may be divided into as many equal angles as required or as dictated by the size and accuracy required.
- *To draw an ellipse using the parallelogram method* (Fig. 2.38), on the axes *ab* and *cd,* construct a parallelogram. Divide *aO* into any number of equal parts, and divide *ae* into the same number of equal parts. Draw lines through points 1 through 4 from points *c* and *d.* The intersection of these lines will be points on the ellipse.
- *To draw a parabola using the parallelogram method* (Fig. 2.39), divide *Oa* and *ba* into the same number of equal parts. From the divisions on *ab,* draw lines converging at *O*. Lines drawn parallel

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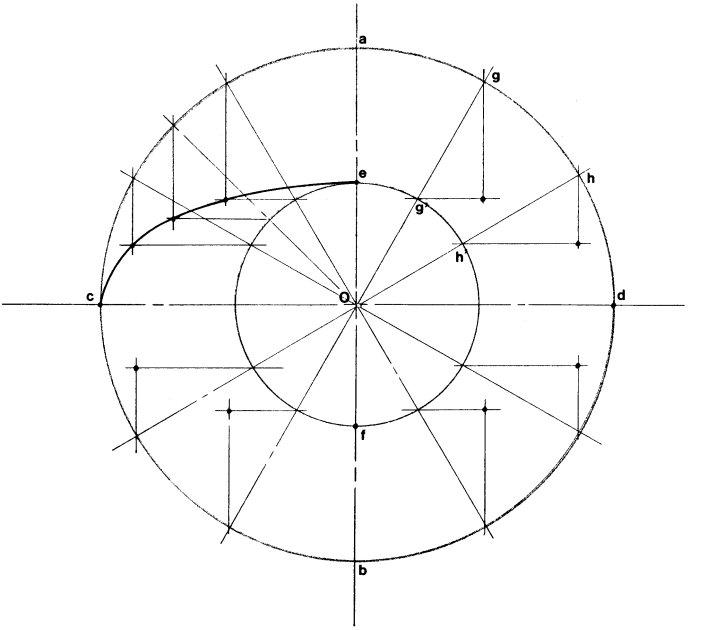

Figure 2.37 Drawing an ellipse.

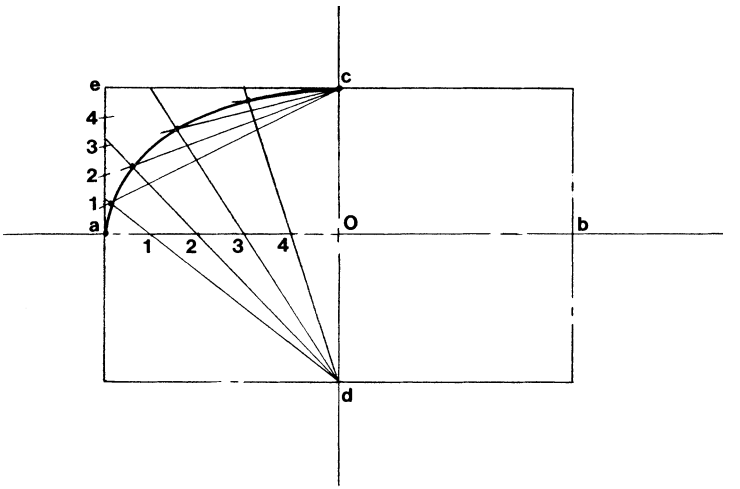

Figure 2.38 An ellipse by the parallelogram method.

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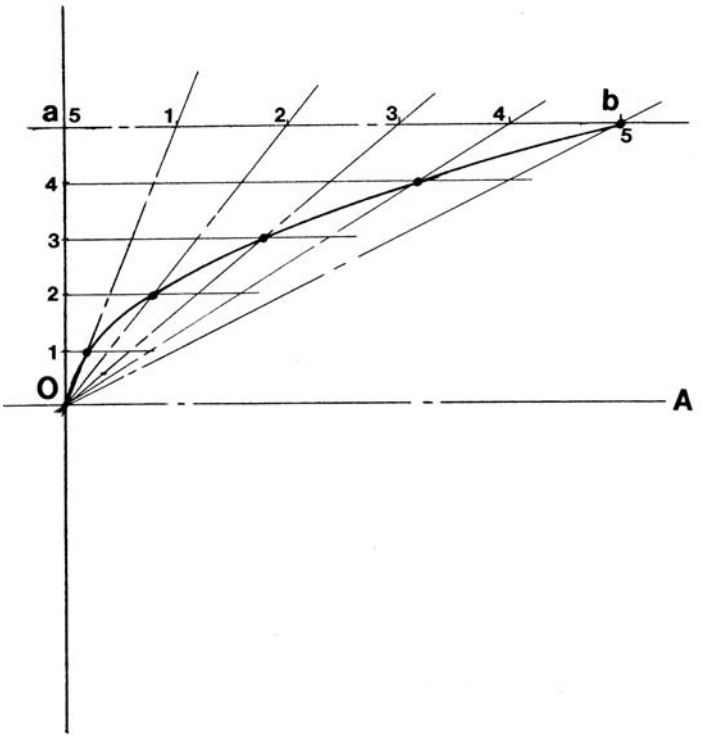

Figure 2.39 A parabola by the parallelogram method.

to line *OA* and intersecting the divisions on *Oa* will intersect the lines drawn from point *O*. These intersections are points on the parabola.

- *To draw a parabola using the offset method* (Fig. 2.40), the parabola may be plotted by computing the offsets from line *O*5. These offsets vary as the square of their distance from point *O*. If *O*5 is divided into five equal parts, distance 1*e* will be ⅕ distance 5*a*. Offset 2*d* will be ⅘ distance 5*a;* offset 3*c* will be ⅗ distance 5*a;* etc.
- *To draw a parabolic envelope* (Fig. 2.41), divide *Oa* and *Ob* into the same number of equal parts. Number the divisions from *Oa* and *Ob*, 1 through 6, etc. The intersection of points 1 and 6, 2 and 5, 3 and 4, 4 and 3, 5 and 2, and 6 and 1 will be points

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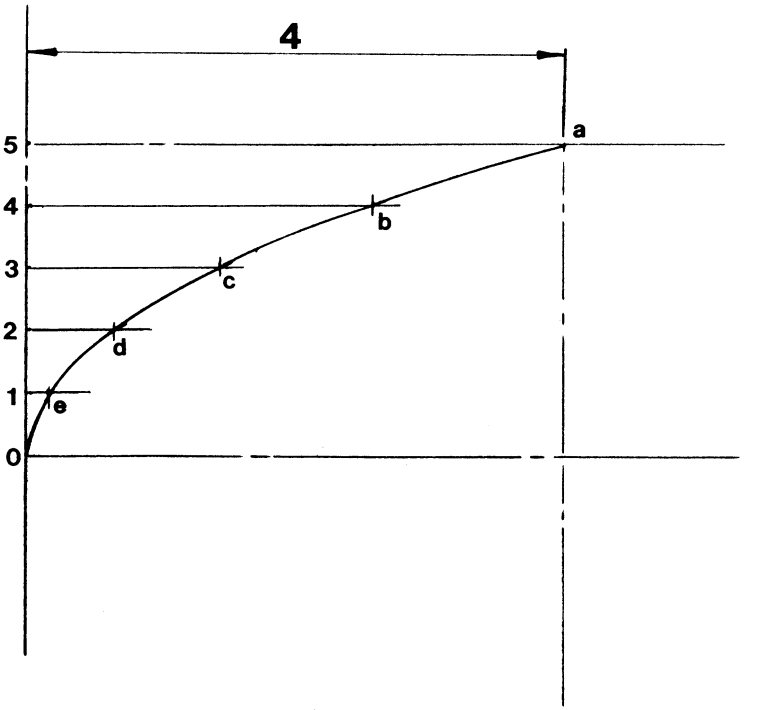

Figure 2.40 A parabola by the offset method.

on the parabola. This parabola's axis is not parallel to either ordinate.

- *To draw a parabola when the focus and directorix are given* (Fig. 2.42), draw axis Op through point f and perpendicular to directorix AB. Through any point k on the axis Op, draw lines parallel to AB. With distance kO as a radius and f as a center, draw an arc intersecting the line through k, thus locating a point on the parabola. Repeat for Oj, Oi, etc.

2.4 Mensuration

Mensuration is the mathematical name for calculating the areas, volumes, lengths of sides, and other geometric parts of standard geometric shapes such as circles, spheres, polygons, prisms, cylinders,

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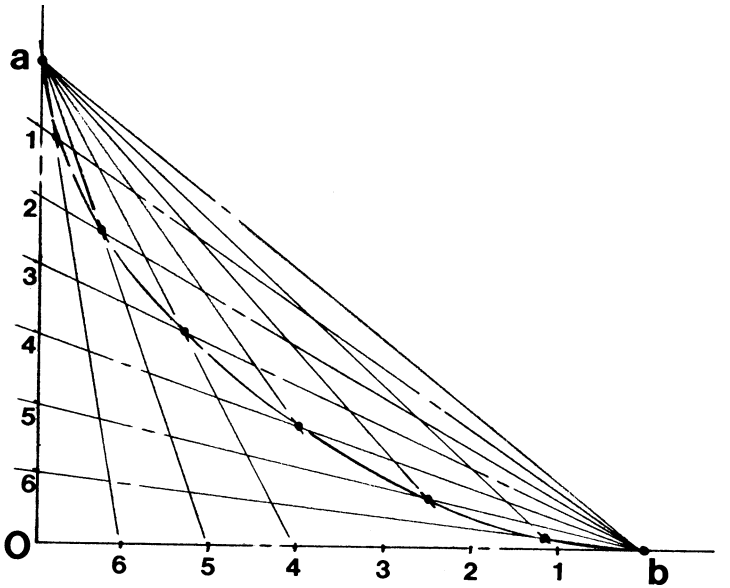

Figure 2.41 A parabolic envelope.

cones, etc. through the use of mathematical equations or formulas. Included here are the most frequently used and important mensuration formulas for the common geometric figures, both plane and solid.

$A = \frac{1}{2}bh$ (Fig. 2.43)

$A = \frac{1}{2}ab\sin C$ (Fig. 2.44)

$A = \sqrt{s(s-a)(s-b)(s-c)}$ where $s = \frac{1}{2}(a+b+c)$

$A = ab$ (Fig. 2.45)

$A = bh$ (Fig. 2.46)

$A = \frac{1}{2}cd$ (Fig. 2.47)

$A = \frac{1}{2}(a+b)h$ (Fig. 2.48)

$$A = \frac{(H+h)a + bh + cH}{2}$$ (Fig. 2.49)

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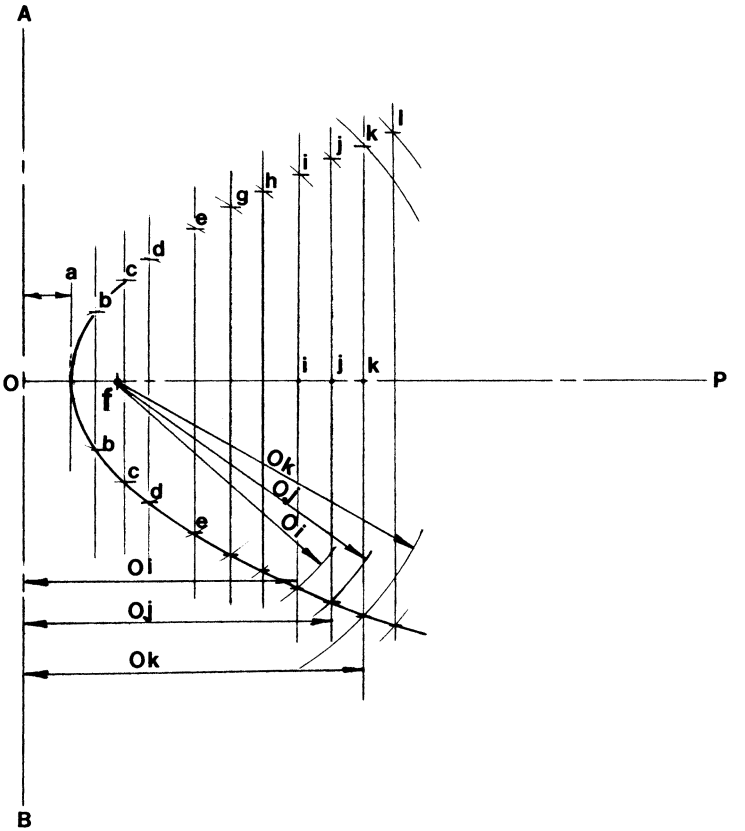

Figure 2.42 A parabolic curve.

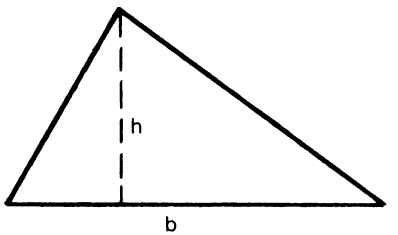

Figure 2.43 Triangle.

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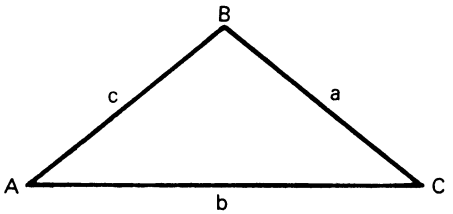

Figure 2.44 Triangle.

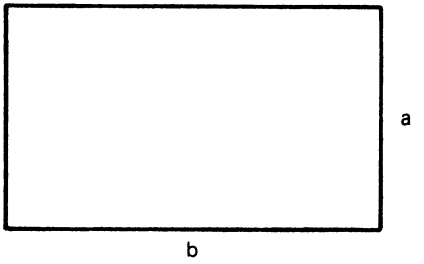

Figure 2.45 Rectangle.

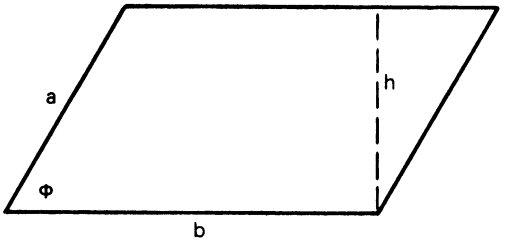

Figure 2.46 Parallelogram.

$$A = \tfrac{1}{4} nL^2 \cot \frac{180}{n} \qquad \text{(Fig. 2.50)}$$

where n = number of sides, and L = length of a side. In a polygon of n sides, each of which is L, the radius of the inscribed circle is

$$r = \frac{L}{2} \cot \frac{180}{n}$$

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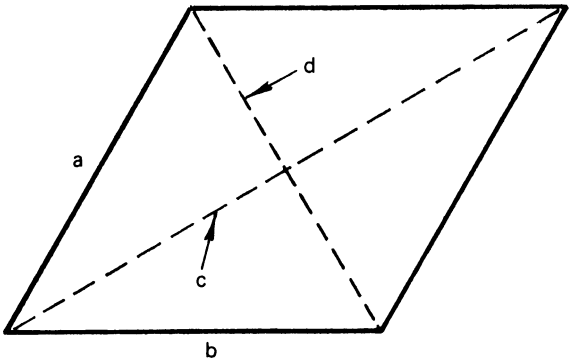

Figure 2.47 Rhombus.

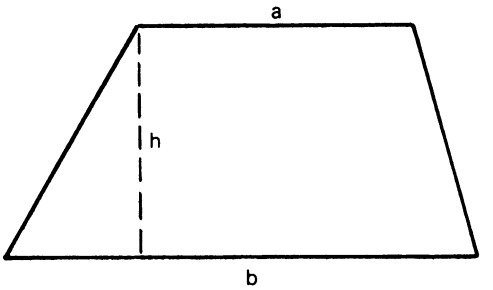

Figure 2.48 Trapezoid.

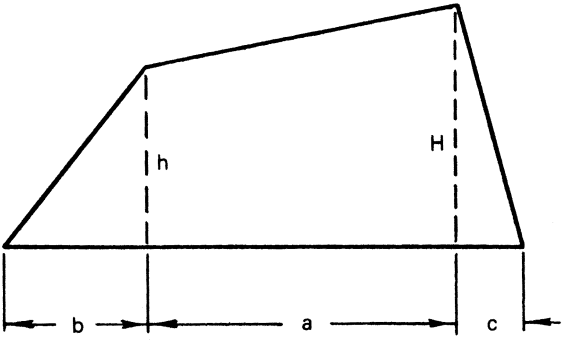

Figure 2.49 Trapezium.

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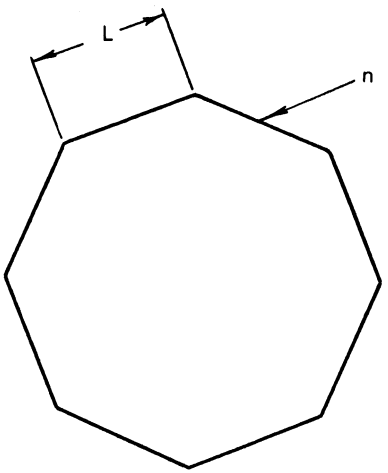

Figure 2.50 Polygon.

and the radius of the circumscribed circle is

$$r_1 = \frac{L}{2}\operatorname{cosec}\frac{180}{n}$$

The radius of a circle inscribed in any triangle whose sides are *a*, *b*, and c is

$$r = \frac{\sqrt{s(s-a)(s-b)(s-c)}}{s} \qquad \text{(Fig. 2.51)}$$

where $s = \frac{1}{2}(a + b + c)$.

The radius of the circumscribed circle is

$$R = \frac{abc}{4s(s-a)(s-b)(s-c)} \qquad \text{(Fig. 2.52)}$$

Area of an inscribed polygon is

$$A = \tfrac{1}{2}nr^2 \sin\frac{2\pi}{n} \qquad \text{(Fig. 2.53)}$$

where r is the radius of the circumscribed circle, and n is the number of sides.

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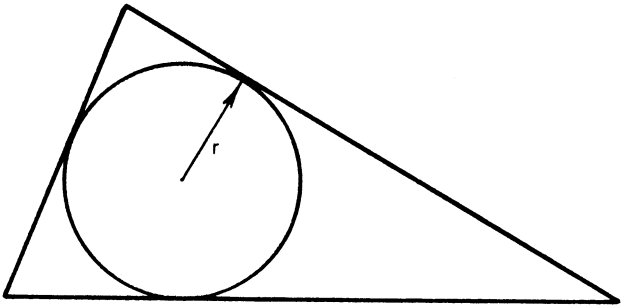

Figure 2.51 Circle inscribed in a triangle.

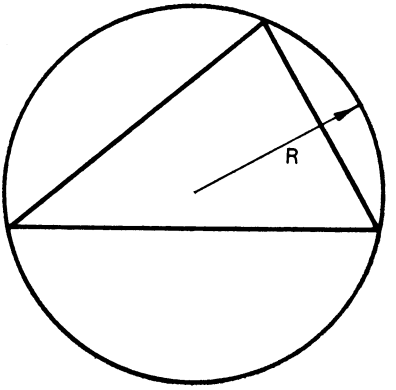

Figure 2.52 Circle circumscribed around a triangle.

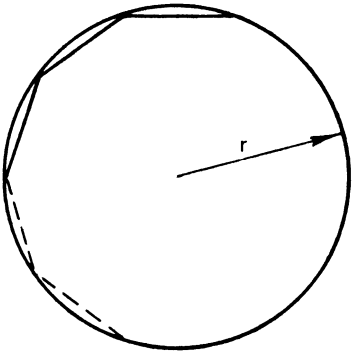

Figure 2.53 Inscribed polygon.

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Area of a circumscribed polygon is

$$A = nR^2 \tan\frac{\pi}{n} \qquad \text{(Fig. 2.54)}$$

where R is radius of the inscribed circle, and n is the number of sides.

Circumference of a circle is

$$C = 2\pi r = \pi d \qquad \text{(Fig. 2.55)}$$

Area of a circle is

$$A = \pi r^2 = \tfrac{1}{4}\pi d^2 \qquad \text{(Fig. 2.56)}$$

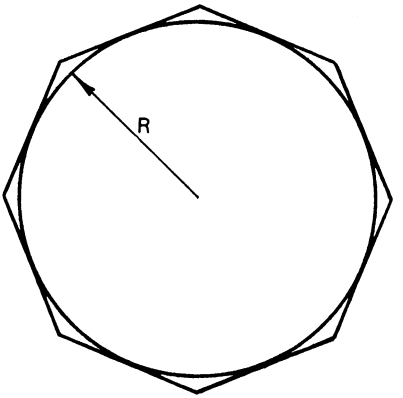

Figure 2.54 Circumscribed polygon.

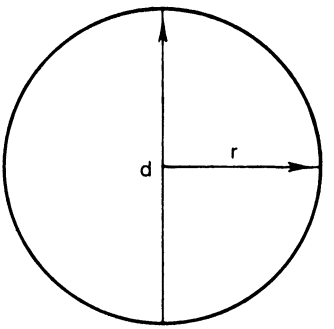

Figure 2.55 Circle.

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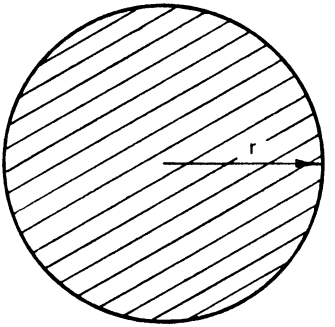

Figure 2.56 Area of a circle.

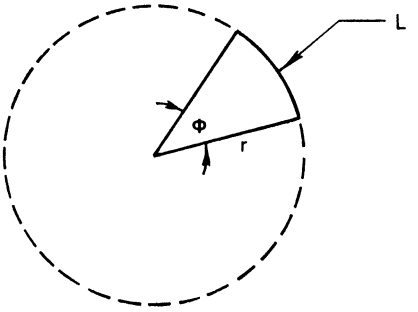

Figure 2.57 Arc length.

Length of arc L is

$$L = \frac{\pi r \phi}{180} \qquad \text{(Fig. 2.57)}$$

where ϕ is in radians, $L = r\phi$.

Length of chord AB is

$$AB = 2r \sin(\tfrac{1}{2}\phi) \qquad \text{(Fig. 2.58)}$$

Area of the sector is

$$A = \frac{r^2 \phi}{360} \qquad \text{or} \qquad A = \frac{rL}{2}$$

where L is the length of the arc.

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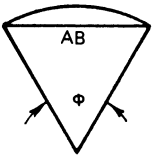

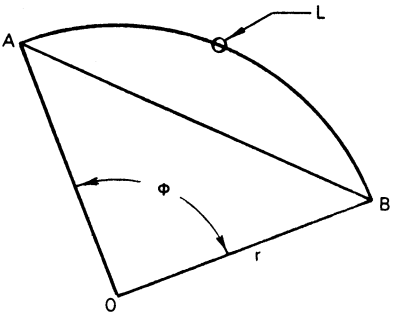

Figure 2.58 Chord.

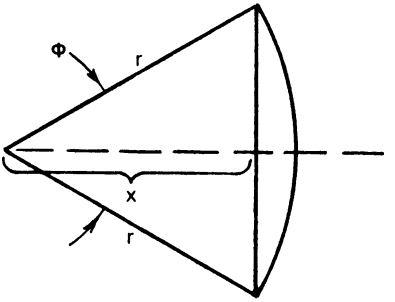

Figure 2.59 Segment.

Area of a segment of a circle is

$$A = \frac{\pi r^2 \phi}{360} - \frac{r^2 \sin \phi}{2} \qquad \text{(Fig. 2.59)}$$

where $\phi = 180° - 2 \arcsin x/r$, and x = perpendicular distance, center to chord. If ϕ is in radians, $A = \frac{1}{2}r^2(\phi - \sin\phi)$.

Area of the ring between circles is

$$A = \pi(R + r)(R - r) \qquad \text{(Fig. 2.60)}$$

Note: The circles need not be concentric.

Circumference of an ellipse is

$$C = 2\pi\sqrt{\frac{a^2 + b^2}{2}} \text{ (approximate)} \qquad \text{(Fig. 2.61)}$$

$$A = \pi ab$$

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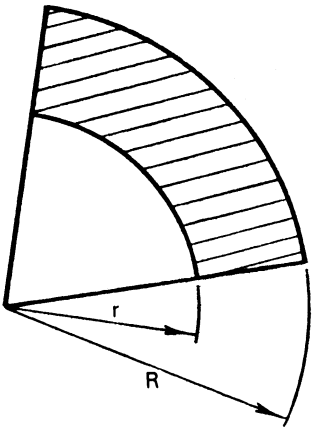

Figure 2.60 Ring between circles.

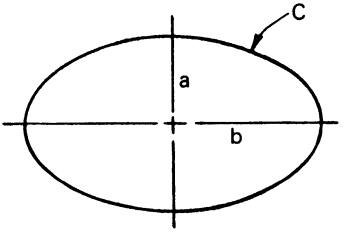

Figure 2.61 Ellipse.

Surface and volume of a sphere are

$$S = 4\pi r^2 = \pi d^2 \qquad \text{(Fig. 2.62)}$$

$$V = \tfrac{4}{3}\pi r^3 = \tfrac{1}{6}\pi d^3$$

Surface and volume of a cylinder are

$$S = 2\pi rh \qquad \text{(Fig. 2.63)}$$

$$V = \pi r^2 h$$

Surface and volume of a cone are

$$S = \pi r\sqrt{r^2 + h^2} \qquad \text{(Fig. 2.64)}$$

$$V = (\pi / 3)r^2 h$$

Area and volume of curved surface of spherical segment are

$$A = 2\pi rh \qquad \text{(Fig. 2.65)}$$

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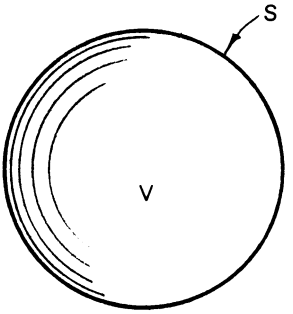

Figure 2.62 Sphere.

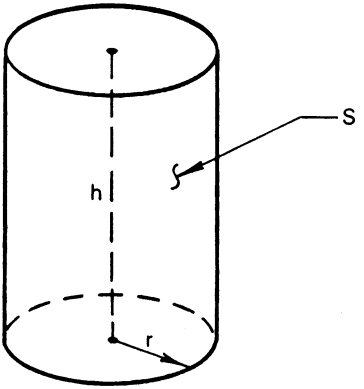

Figure 2.63 Cylinder.

$$V = (\tfrac{1}{3}\pi h^2)(3r - h)$$

When a is the radius of the base of the segment,

$$V = (\tfrac{1}{4}\pi h)(h^2 + 3a^2)$$

Surface area and volume of the frustum of a cone are

$$S = \pi(r_1 + r_2)\sqrt{h^2 + (r_1 - r_2)^2} \qquad \text{(Fig. 2.66)}$$

$$V = \frac{h}{3}(r_1^2 + r_1 r_2 + r_2^2)\pi$$

Area and volume of a truncated cylinder are

$$A = \pi r(h_1 + h_2) \qquad \text{(Fig. 2.67)}$$

$$V = 1.5708r^2(h_1 + h_2)$$

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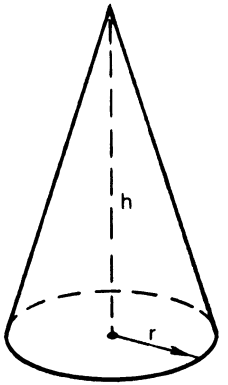

Figure 2.64 Cone.

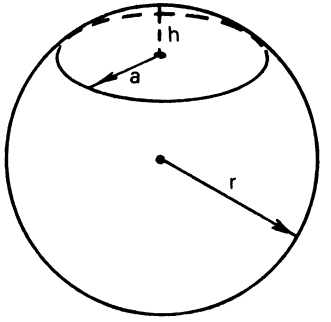

Figure 2.65 Spherical segment.

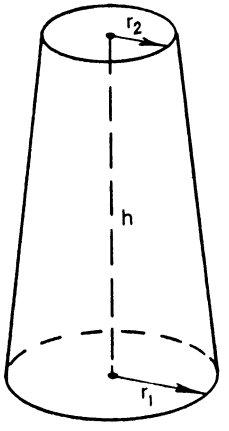

Figure 2.66 Frustum of a cone.

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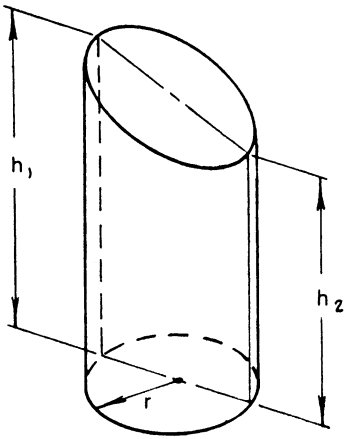

Figure 2.67 Truncated cylinder.

Area and volume of a portion of a cylinder (base edge = diameter) are

$$A = 2rh \qquad \text{(Fig. 2.68)}$$

$$V = \tfrac{2}{3}r^2h$$

Area and volume of a portion of a cylinder (special cases) are

$$A = \frac{h(ad \pm c \times \text{perimeter of base})}{r \pm c} \qquad \text{(Fig. 2.69)}$$

$$V = \frac{h(\tfrac{2}{3}a^3 \pm cA)}{r \pm c}$$

where d = diameter of base circle. Use $+c$ when the base area is larger than half the base circle; use $-c$ when the base area is smaller than half the base circle.

Volume of a wedge is

$$V = \frac{(2b + c)ah}{6} \qquad \text{(Fig. 2.70)}$$

Area and volume of a spherical zone are

$$A = 2\pi rh \qquad \text{(Fig. 2.71)}$$

$$V = 0.5236h\left(\frac{3c_1^2}{4} + \frac{3c_2^2}{4} + h^2\right)$$

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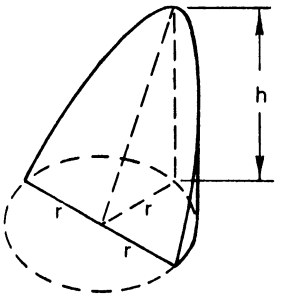

Figure 2.68 Portion of a cylinder.

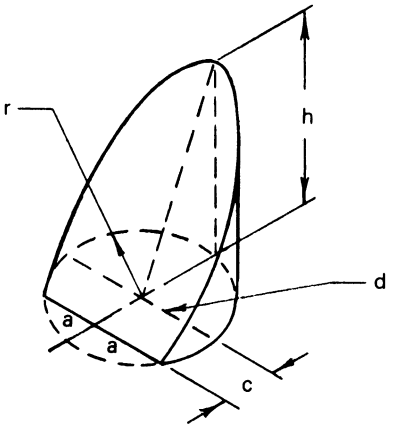

Figure 2.69 Portion of a cylinder.

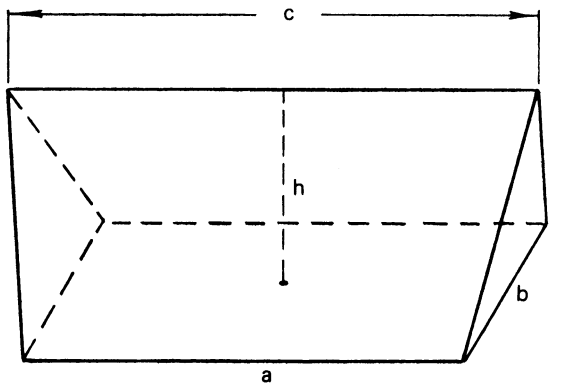

Figure 2.70 Wedge.

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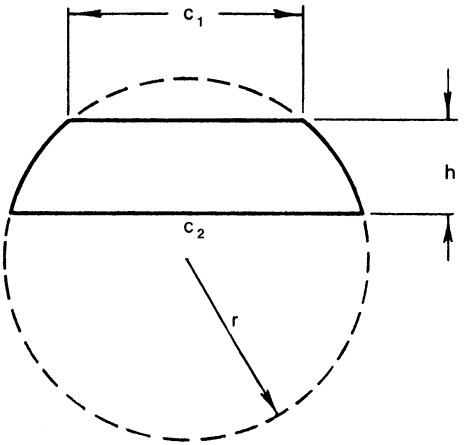

Figure 2.71 Spherical zone.

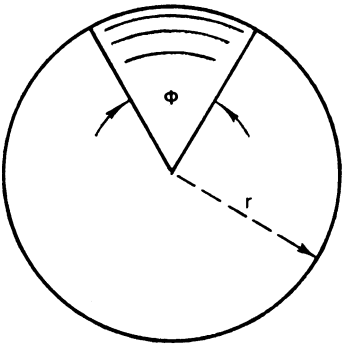

Figure 2.72 Spherical wedge.

Area and volume of a spherical wedge are

$$A = \frac{\phi}{360} 4\pi r^2 \qquad \text{(Fig. 2.72)}$$

$$V = \frac{\phi}{360} \frac{4\pi r^3}{3}$$

The volume of a paraboloid is

$$V = \frac{\pi r^2 h}{2} \qquad \text{(Fig. 2.73)}$$

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Mathematics for Machinists and Metalworkers

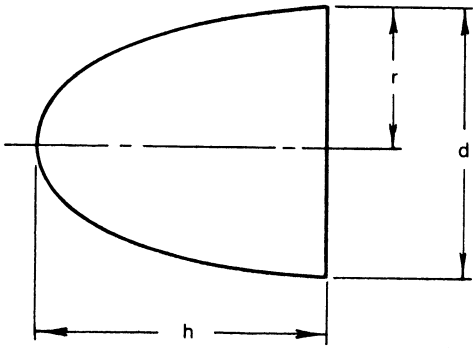

Figure 2.73 Paraboloid.

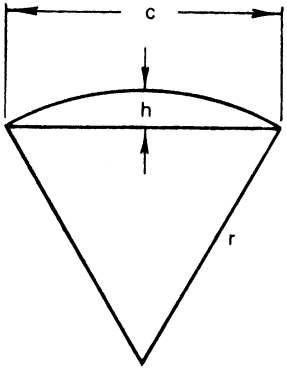

Figure 2.74 Spherical sector.

Area and volume of a spherical sector are

$$A = r\left(2h + \frac{c}{2}\right) \qquad \text{(total area)} \qquad \text{(Fig. 2.74)}$$

$$V = \frac{2\pi r^2 h}{3}$$

where $c = 2\sqrt{h(2r-h)}$.

Area and volume of a spherical segment are

$$A = 2\pi rh \qquad \text{(spherical surface)} \qquad \text{(Fig. 2.75)}$$

$$A = \pi\left(\frac{c^2}{4} + h^2\right) \qquad c = 2\sqrt{h(2r-h)} \qquad r = \frac{c^2 + 4h^2}{8h}$$

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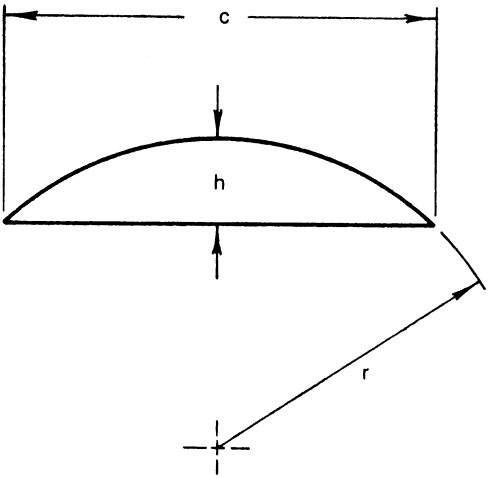

Figure 2.75 Spherical segment.

$$V = \pi h^2 \left(r - \frac{h}{3} \right)$$

Area and volume of a torus are

$A = 4\pi^2 cr$ (total surface) (Figs. 2.76 and 2.77)

$V = 2\pi^2 cr^2$ (total volume)

For properties of the circle, see Fig. 2.78.

2.5 Percentage Calculations

Percentage calculation procedures have many applications in machining, design, and metalworking problems. Although the procedures are relatively simple, it is easy to make mistakes in the manipulations of the numbers involved.

Ordinarily, 100 percent of any quantity is represented by the number 1.00, meaning the total quantity. Thus, if we take 50 percent of any quantity, or any multiple of 100 percent, it *must* be expressed as a decimal:

$$1\% = 0.01$$

$$10\% = 0.10$$

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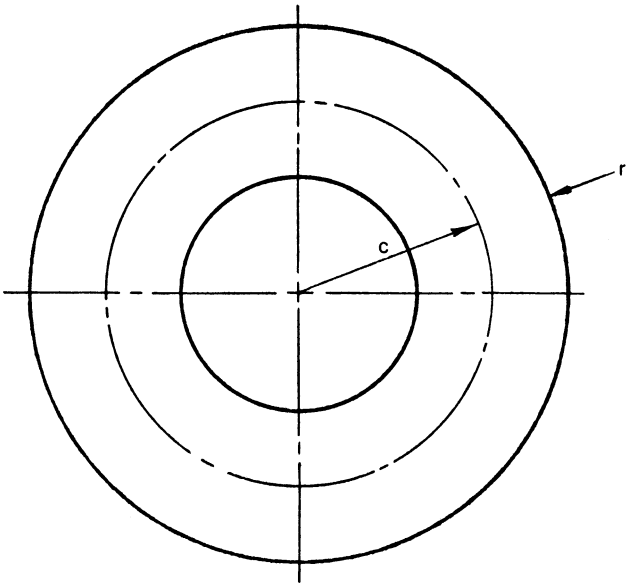

Figure 2.76 Torus.

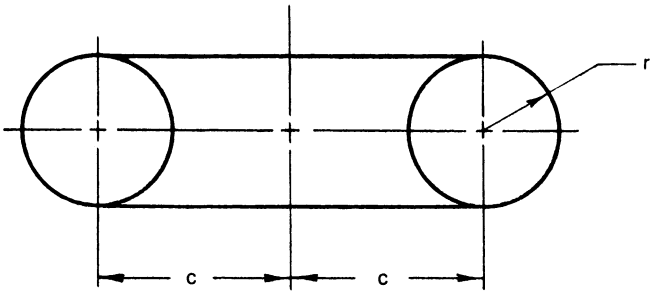

Figure 2.77 Torus.

$$65.5\% = 0.655$$

$$145\% = 1.45$$

In effect, we are dividing the percentage figure, such as 65.5 percent, by 100 to arrive at the decimal equivalent required for calculations.

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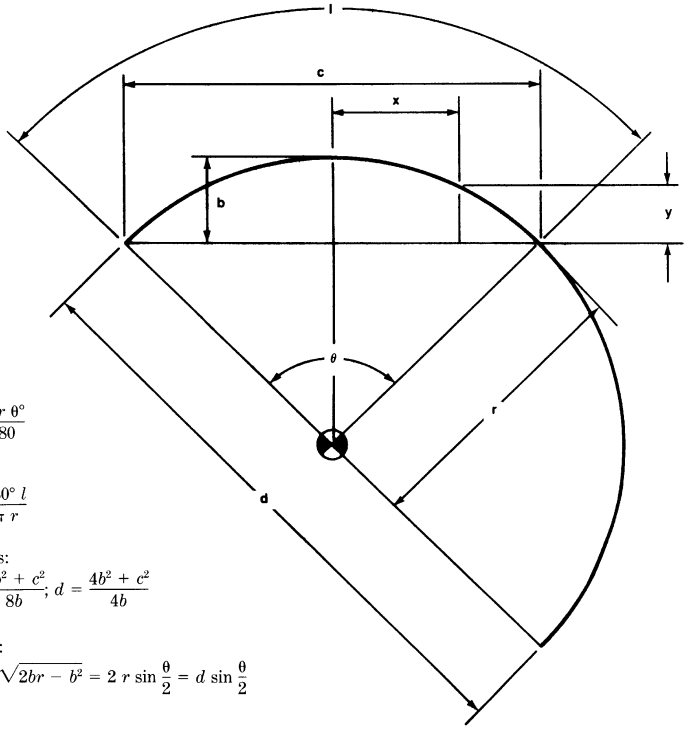

Arc:

$$l = \frac{\pi\, r\, \theta^\circ}{180}$$

Angle:

$$\theta = \frac{180^\circ\, l}{\pi\, r}$$

Radius:

$$r = \frac{4b^2 + c^2}{8b};\quad d = \frac{4b^2 + c^2}{4b}$$

Chord:

$$c = 2\sqrt{2br - b^2} = 2\, r \sin\frac{\theta}{2} = d \sin\frac{\theta}{2}$$

Rise:

$$b = r - \frac{1}{2}\sqrt{4r^2 - c^2} = \frac{c}{2}\tan\frac{\theta}{4} = 2\, r \sin^2\frac{\theta}{4}$$

Rise:

$$b = r + y - \sqrt{r^2 - x^2}$$

where $y = b - r + \sqrt{r^2 - x^2}$ and $x = \sqrt{r^2 - (r + y - b)^2}$.

Figure 2.78 Properties of the circle.

Let us take a percentage of a given number:

$$45\% \text{ of } 136.5 = 0.45 \times 136.5 = 61.425$$

$$33.5\% \text{ of } 235.7 = 0.335 \times 235.7 = 78.9595$$

Let us now compare two arbitrary numbers, 33 and 52, as an illustration:

$$\frac{52 - 33}{33} = 0.5758$$

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Thus the number 52 is 57.58 percent larger than the number 33. We also can say that 33 increased by 57.58 percent is equal to 52; that is, $0.5758 \times 33 + 33 = 52$. Now

$$\frac{52 - 33}{52} = 0.3654$$

Thus the number 52 minus 36.54 percent of itself is 33. We also can say that 33 is 36.54 percent less than 52; that is, $0.3654 \times 52 = 19$ and $52 - 19 = 33$. The number 33 is what percent of 52? That is, $33/52 = 0.6346$. Therefore, 33 is 63.46 percent of 52.

2.6 Decimal Equivalents and Millimeter Chart (see Fig. 2.79)

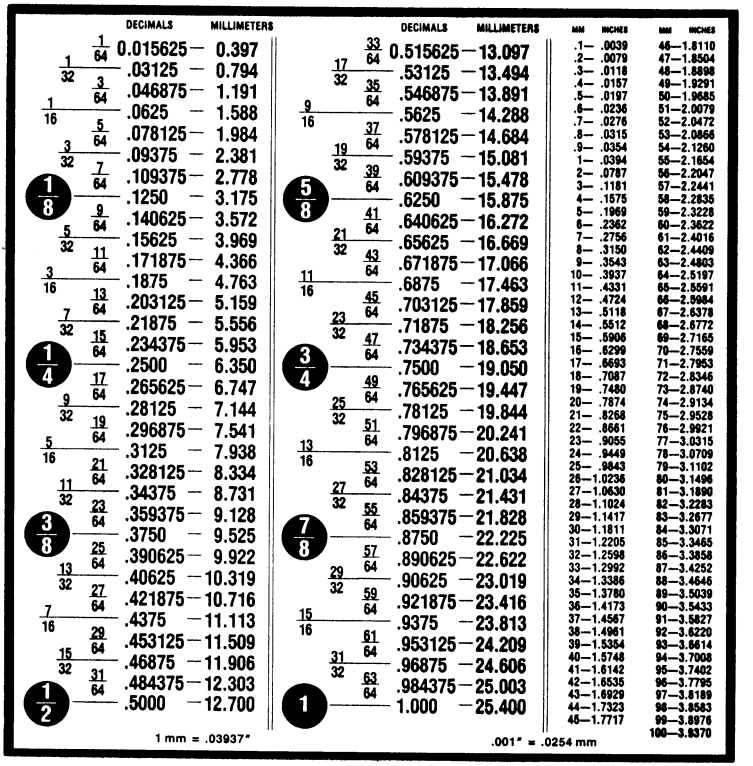

Figure 2.79 Decimal equivalents and millimeters.

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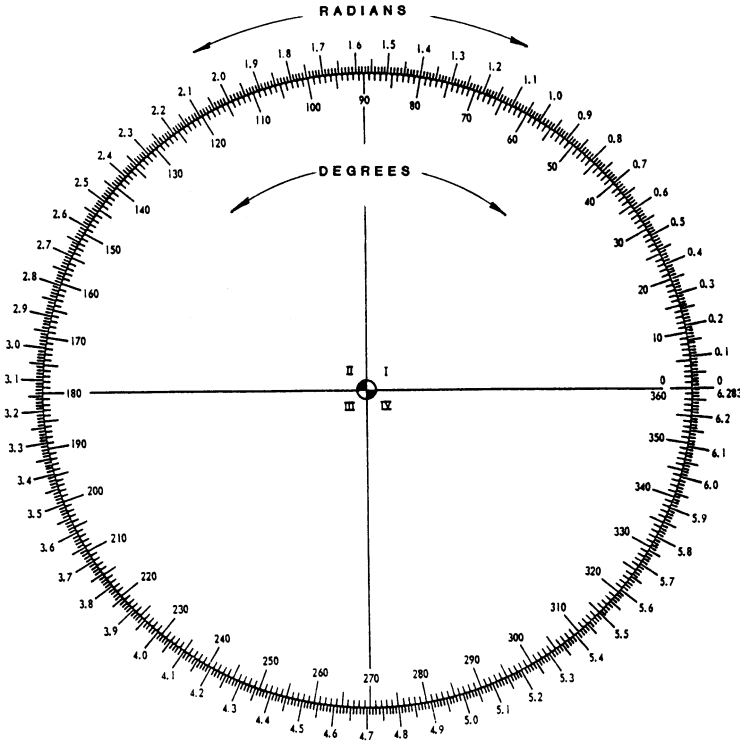

Figure 2.80 Degrees to radians conversion chart.

2.7 Degrees and Radians Chart (see Fig. 2.80)

2.8 Mathematical Signs and Symbols (see Table 2.1)

2.9 Greek Alphabet (see Table 2.2)

2.10 Sine Bar and Sine Plate Calculations

Sine bar procedures. Referring to Fig. 2.81, find the sine bar–setting height for an angle of 34°25′ using a 5-in sine bar.

$$\sin 34°25' = x/5 \qquad (34°25' = 34.416667 \text{ decimal degrees})$$

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TABLE 2.1 Mathematical Signs and Symbols

+	Plus, positive
–	Minus, negative
× or ·	Times, multiplied by
÷ or /	Divided by
=	Is equal to
≡	Is identical to
≅	Is congruent to or approximately equal to
~	Is approximately equal to or is similar to
< and ≮	Is less than, is not less than
> and ≯	Is greater than, is not greater than
≠	Is not equal to
±	Plus or minus, respectively
∓	Minus or plus, respectively
α	Is proportional to
→	Approaches, e.g., as $x \to 0$
≤, ≦	Less than or equal to
≥, ≧	More than or equal to
∴	Therefore
:	Is to, is proportional to
Q.E.D.	Which was to be proved, end of proof
%	Percent
#	Number
@	At
∠ or ⦟	Angle
° ′ ″	Degrees, minutes, seconds
∥,//	Parallel to
⊥	Perpendicular to
e	Base of natural logs, 2.71828 . . .
π	Pi, 3.14159 . . .
( )	Parentheses
[ ]	Brackets
{ }	Braces
′	Prime, $f'(x)$
″	Double prime, $f''(x)$
$\sqrt{}$, $\sqrt[n]{}$	Square root, *n*th root
$1/x$ or x^{-1}	Reciprocal of x
!	Factorial
∘	Infinity
Δ	Delta, increment of
∂	Curly "d," partial differentiation
Σ	Sigma, summation of terms
Π	The product of terms, product
arc	As in arcsine (the angle whose sine is)
f	Function, as $f(x)$
rms	Root mean square
$\lvert x \rvert$	Absolute value of x
i	For –1
j	Operator, equal to –1

TABLE 2.2 The Greek Alphabet

α	A	alpha	ι	I	iota	ρ	P	rho
β	B	beta	κ	κ	kappa	σ	Σ	sigma
γ	Γ	gamma	λ	Λ	lambda	τ	T	tau
δ	Δ	delta	μ	M	mu	υ	Y	upsilon
ε	E	epsilon	ν	N	nu	ϕ	Φ	phi
ζ	Z	zeta	φ	Ξ	xi	χ	X	chi
η	H	eta	o	O	omicron	ψ	Ψ	psi
θ	Θ	theta	π	Π	pi	ω	Ω	omega

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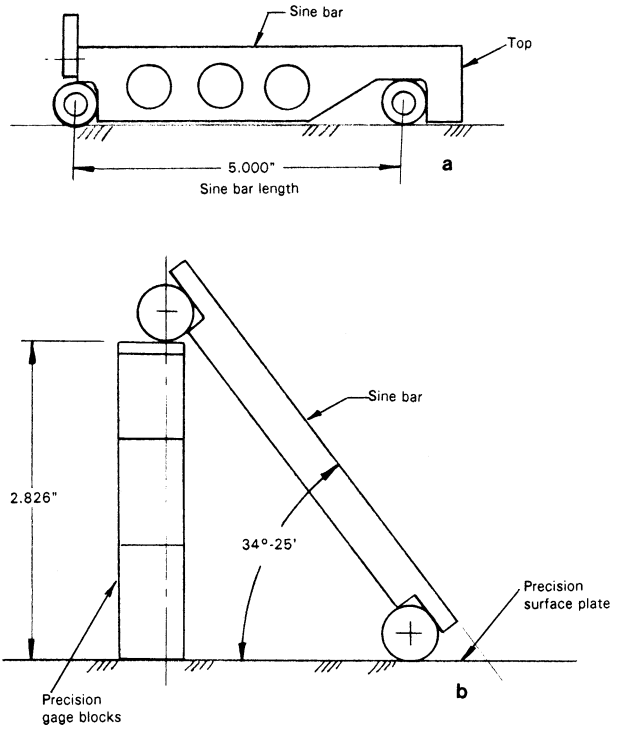

Figure 2.81 (*a*) Sine bar. (*b*) Sine bar.

$$\sin 34.416667^\circ = x/5$$

$$x = 5 \times 0.565207$$

$$x = 2.826 \text{ in}$$

Set the sine bar height with Jo-blocks or precision blocks to 2.826 in.

From this example it is apparent that the setting height can be found for any sine bar length simply by multiplying the length of the sine bar times the natural sine value of the required angle. The simplicity, speed, and accuracy possible for setting sine bars with the aid of the pocket calculator render sine bar tables obsolete. No sine bar table will give you the required setting height for such an angle as 42°17′26″, but by using the calculator proce-

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dure, this becomes a routine, simple process with less chance for errors.

Method

1. Convert the required angle to decimal degrees.
2. Find the natural sine of the required angle.
3. Multiply the natural sine of the angle by the length of the sine bar to find the bar-setting height (see Fig. 2.81).

Formulas for finding angles. Refer to Fig. 2.82 when angles α and ϕ are known to find angles *X, A, B,* and *C*.

$$\tan X = \tan \alpha \cos \phi$$

$$\sin C = \cos \alpha / \cos X$$

$$\text{Angle } B = 180^\circ - (\text{angle } A + \text{angle } C)$$

$$\tan A = \frac{\sin \alpha \sin C}{\sin \phi - (\sin \alpha \cos C)}$$

$$D = \text{true angle}$$

$$\tan D = \tan \phi \sin T$$

$$\tan C = \frac{\sin D}{\tan \theta}$$

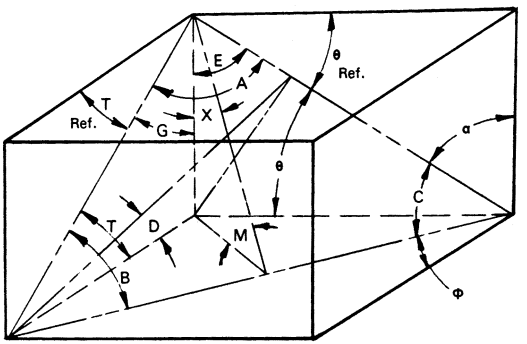

Figure 2.82 Finding the unknown angles.

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$$\tan M = \sqrt{(\tan \theta)^2 + (\tan T)^2}$$

$$\cos A = \cos E \cos G$$

$$\cos A = \sin \theta \sin T$$

Formulas for finding true and apparent angles. See Fig. 2.83*a*, where α = apparent angle, θ = true angle, and ϕ = angle of rotation.

Note: Apparent angle α is *OA* triangle projected onto plane *OB*. See also Fig. 2.83*b*.

$$\tan \theta = K/L$$

$$\tan \alpha = K/(L \cos \phi)$$

$$\tan \alpha \cos \phi = K/L$$

$$K/L = \tan \theta = \cos \phi \tan \alpha$$

or

$$\tan \theta = \cos \phi \tan \alpha$$

and

$$\tan \alpha = \tan \theta / \cos \phi$$

The three-dimensional relationships shown for the angles and triangles in the preceding figures and formulas are of importance and should be understood. This will help in the setting of compound sine plates when it is required to set a compound angle.

Setting compound sine plates. For setting two known angles at 90° to each other, proceed as shown in Fig. 2.84.

Example: First angle = 22.45°. Second angle = 38.58° (see Fig. 2.84). To find the amount the intermediate plate must be raised from the base plate (*X* dimension in Fig. 2.84*b*) to obtain the desired first angle,

1. Find the natural cosine of the second angle (38.58°), and multiply this times the natural tangent of the first angle (22.45°).
2. Find the arctangent of this product, and then find the natural sine of this angle.

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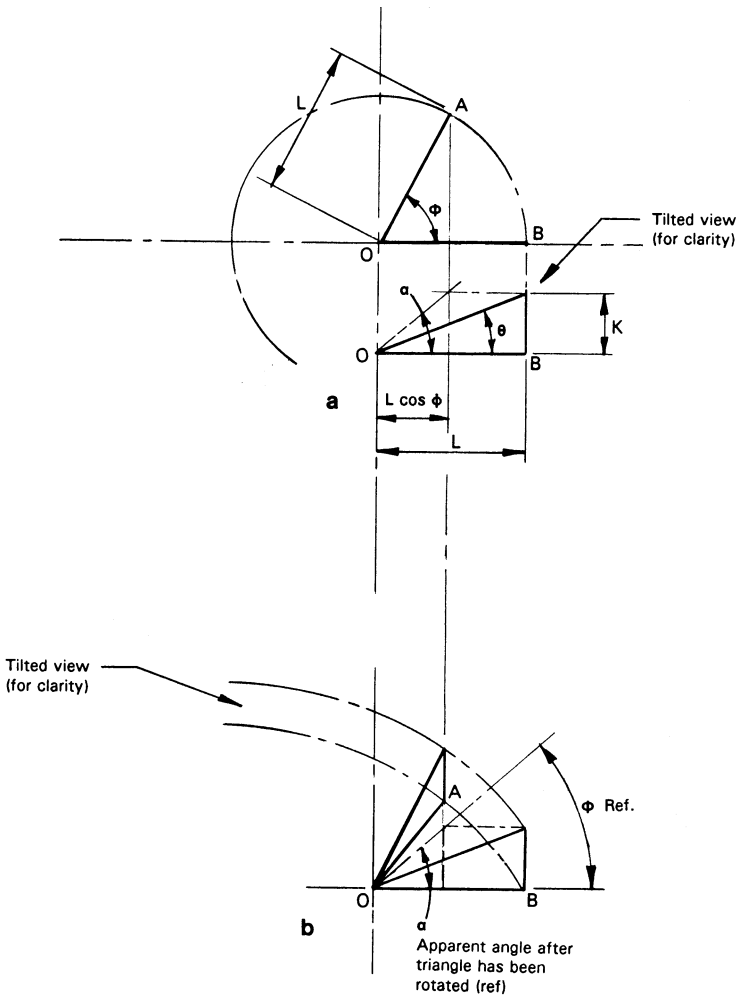

Figure 2.83 True and apparent angles.

3. This natural sine is now multiplied by the length of the sine plate to find the X dimension in Fig. 2.84*b* to which the intermediate plate must be set.
4. Set up the Jo-blocks to equal the X dimension, and set them in position between the base plate and the intermediate plate.

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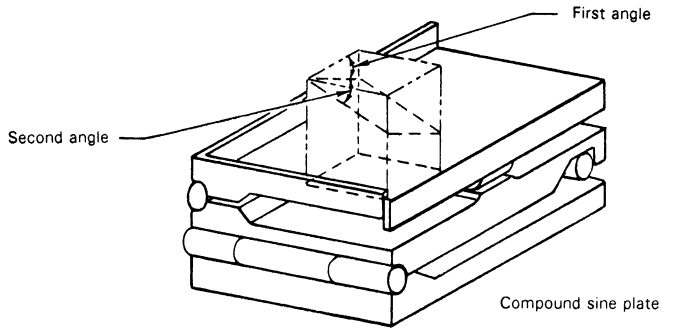
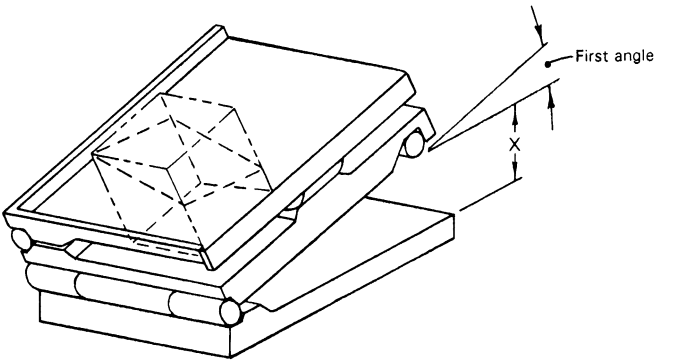
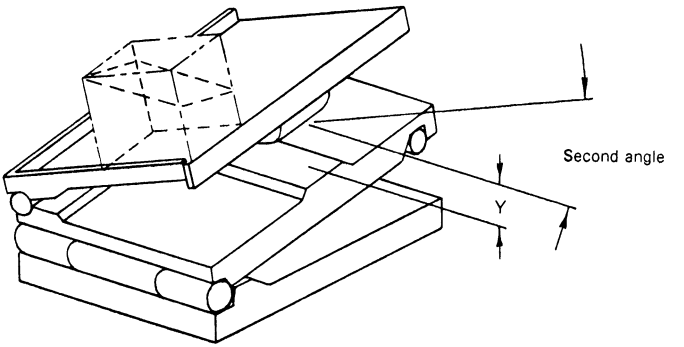


(a)



(b)



(c)

Figure 2.84 Setting angles on a sine plate.

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$$\cos 38.58^\circ = 0.781738$$

$$\tan 22.45^\circ = 0.413192$$

$$0.781738 \times 0.413192 = 0.323008$$

$$\arctan 0.323008 = 17.900872^\circ$$

$$\sin 17.900872^\circ = 0.307371$$

$$0.307371 \times 10 \text{ in (for 10-in sine plate)} = 3.0737 \text{ in}$$

Therefore, set X dimension to 3.074 in (to three decimal places).

To find the amount the top plate must be raised (the Y dimension in Fig. 2.84*c*) above the intermediate plate to obtain the desired second angle,

1. Find the natural sine of the second angle, and multiply this by the length of the sine plate.
2. Set up the Jo-blocks to equal the Y dimension, and set them in position between the top plate and the intermediate plate.

$$\sin 38.58^\circ = 0.632607$$

$$0.632607 \times 10 \text{ in (for l0-in sine plate)} = 6.32607$$

Therefore, set the Y dimension to 6.326 in (to three decimal places).

2.11 Solutions to Problems in Machining and Metalworking

The following sample problems will show in detail the importance of trigonometry and basic algebraic operations as they apply to machining and metalworking. By using the methods and procedures shown in this chapter of the *Handbook,* you will be able to solve many basic and complex machining and metalworking problems.

Taper (Fig. 2.85). Solve for x if y is given; solve for y if x is given; solve for d. Use the tangent function:

$$\tan A = y/x$$

$$d = D - 2y$$

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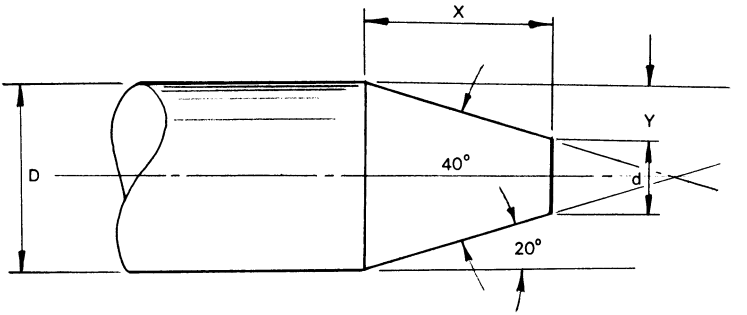

Figure 2.85 Taper.

where A = taper angle
D = outside diameter of rod
d = diameter at end of taper
x = length of taper
y = drop of taper

Example: If the rod diameter = 0.9375 diameter, taper length = 0.875 = x, and taper angle = 20° = angle A, find y and d from

$$\tan 20° = y/x$$

$$y = x \tan 20°$$

$$= 0.875(0.36397) = 0.318$$

$$d = D - 2y$$

$$= 0.9375 - 2(0.318)$$

$$= 0.9375 - 0.636$$

$$= 0.3015$$

Countersink depths (three methods for calculating)

Method 1: To find the tool, travel y from the top surface of the part for a given countersink finished diameter at the part surface:

$$y = \frac{D/2}{\tan A/2} \qquad \text{(Fig. 2.86)}$$

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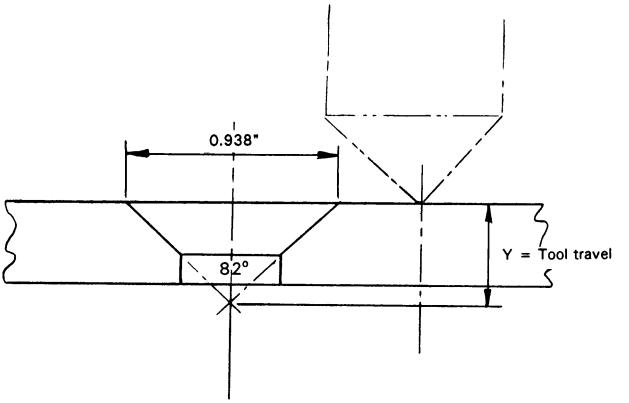

Figure 2.86 Countersink depth.

where D = finished countersink diameter
A = countersink angle
y = tool advance from surface of part

$$y = \frac{0.938/2}{\tan 41^\circ} = \frac{0.469}{0.869} = 0.5397, \text{ or } 0.540$$

Method 2: To find the tool travel from the edge of the hole (Fig. 2.87), where D = finished countersink diameter, H = hole diameter, and A = ½ countersink angle, 41°,

$$\tan A = x/y$$

$$y = x/\tan A \qquad \text{or} \qquad x/(\tfrac{1}{2} \text{ countersink angle})$$

First, find x from

$$D = H + 2x$$

If $D = 0.875$ and $H = 0.500$,

$$0.875 = 0.500 + 2x$$

$$2x = 0.375$$

$$x = 0.1875$$

Now solve for y, the tool advance:

$$y = x/\tan A$$

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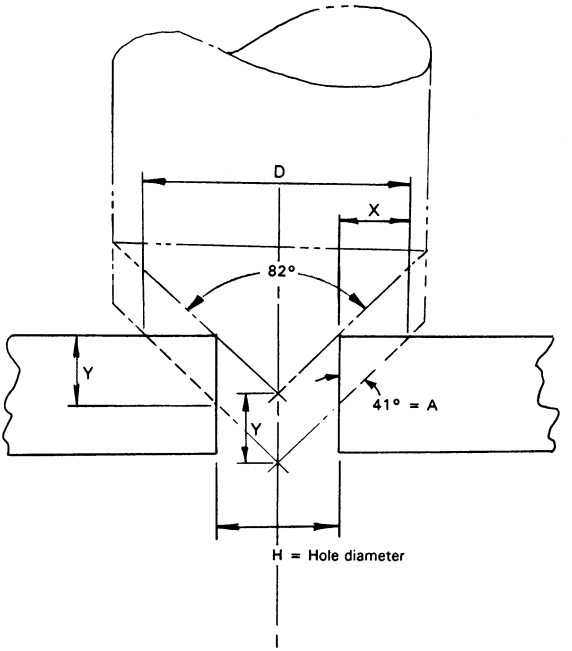

Figure 2.87 Tool travel in countersinking.

$= 0.1875/\tan 41°$

$= 0.1875/0.8693$

$= 0.2157$, or 0.216 (tool advance from edge of hole)

Method 3: To find tool travel from the edge of the hole (Fig. 2.88), where D = finished countersink diameter, d = hole diameter, ϕ = ½ countersink angle, and H = countersink tool advance from edge of hole,

$$H = \tfrac{1}{2}(D - d)\ \text{cotan}\ \phi \qquad \text{or} \qquad H = \frac{D-d}{2\tan\theta}$$

(Remember that cotan $\phi = 1/\tan\phi$ or $\tan\phi = 1/\text{cotan}\ \phi$.)

Finding taper angle α. Given dimensions shown in Fig. 2.89, find angle α and length x. First, find angle α from

$$y = \frac{1.875 - 0.500}{2} = \frac{1.375}{2} = 0.6875$$

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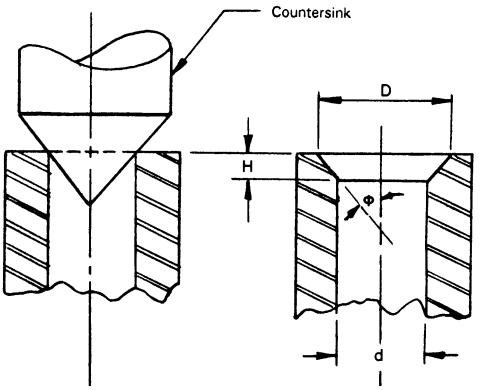

Figure 2.88 Tool travel from the edge of the hole.

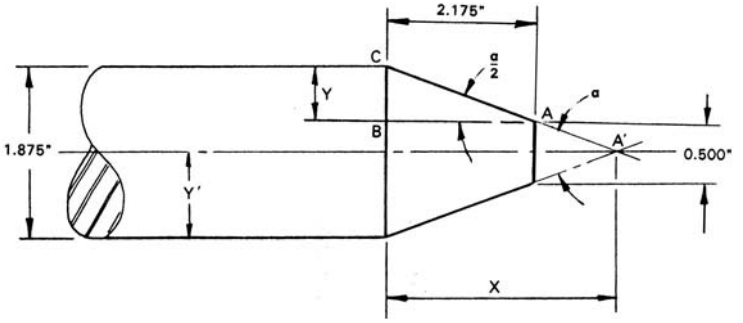

Figure 2.89 Finding taper angle α.

Then solve triangle ABC for ½ angle α:

$$\tan \frac{1}{2}\alpha = \frac{0.6875}{2.175} = 0.316092$$

$$\text{Arctan } ½\alpha = 0.316092$$

$$½\alpha = 17.541326°$$

$$\text{Angle } \alpha = 35.082652°$$

Then solve triangle $A'B'C'$, where $y' = 0.9375$ or ½ diameter of rod:

$$\text{Angle } C = 90° - 17.541326°$$

$$= 72.458674°$$

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Now the x dimension is found from

$$\tan \tfrac{1}{2}\alpha = 0.9375/x$$

$$x = 0.9375/\tan \tfrac{1}{2}\alpha$$

$$= 2.966 \text{ (side } A'B' \text{ or length } x)$$

Compound angles. A solid geometric figure consisting of several plane right triangles contains a compound angle. Each of these right triangles contains one of the angles of the compound angle, and one of these angles is called the *true angle.* The true angle of inclination of a plane to a reference plane is called the *dihedral angle.* Figure 2.90 shows a typical triangular pyramid in which all four faces are right triangles. Most of the solids encountered in actual practice may be reduced to this type of pyramid by drawing a plane of symmetry. The unknown angle then may be calculated from any two known angles that lie in adjacent faces of the pyramid.

The trigonometric solutions for all the compound angles of Fig. 2.90 may be calculated from the following trigonometric relationships:

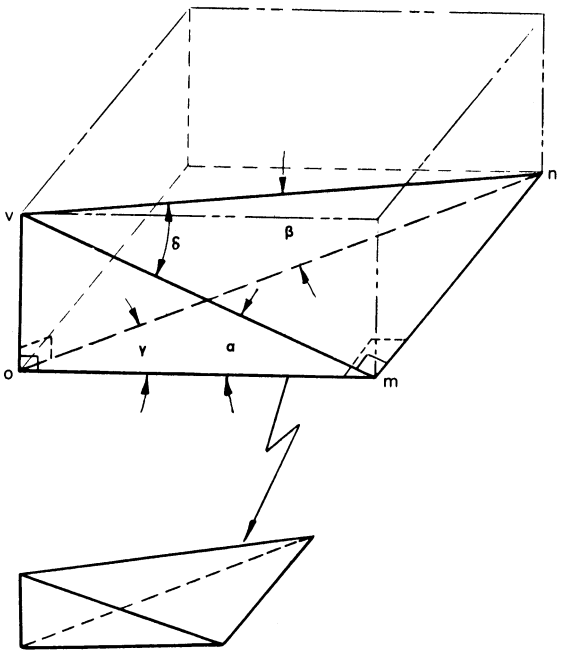

Figure 2.90 Compound angles.

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Mathematics for Machinists and Metalworkers

Solutions To Compound Angles

Given	To find	Equation
α and β	γ	$\cos\gamma = \dfrac{\tan\beta}{\tan\alpha}$
α and β	δ	$\cos\delta = \dfrac{\sin\beta}{\sin\alpha}$
α and γ	β	$\tan\beta = \cos\gamma\tan\alpha$
α and γ	δ	$\tan\delta = \cos\alpha\tan\gamma$
α and δ	β	$\sin\beta = \sin\alpha\cos\delta$
α and δ	γ	$\tan\gamma = \dfrac{\tan\delta}{\cos\alpha}$
β and γ	α	$\tan\alpha = \dfrac{\tan\beta}{\cos\gamma}$
β and γ	δ	$\sin\delta = \cos\beta\sin\gamma$
β and δ	α	$\sin\alpha = \dfrac{\sin\beta}{\cos\delta}$
β and δ	γ	$\sin\gamma = \dfrac{\sin\delta}{\cos\beta}$
γ and δ	α	$\cos\alpha = \dfrac{\tan\delta}{\tan\gamma}$
γ and δ	β	$\cos\beta = \dfrac{\sin\delta}{\sin\gamma}$

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Source: McGraw-Hill Machining and Metalworking Handbook

Chapter

3

U.S. Customary and Metric (SI) Measures and Conversions

3.1 Conversions for Length, Pressure, Velocity, Volume, and Weight

To convert from:	To:	Multiply by:
	Length	
Centimeters	Inches	0.3937
Centimeters	Yards	0.01094
Feet	Inches	12.0
Feet	Meters	0.30481
Feet	Yards	0.333
Inches	Centimeters	2.540
Inches	Feet	0.08333
Inches	Meters	0.02540
Inches	Microns	25,400.
Inches	Millimeters	25.400
Inches	Yards	0.02778
Meters	Feet	3.2809
Meters	Yards	1.0936
Microns	Inches	0.0000394
Microns	Meters	0.000001
Millimeters	Inches	0.03937

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To convert from:	to:	Multiply by:
Rods	Meters	5.0292
Yards	Centimeters	91.44
Yards	Feet	3.0
Yards	Inches	36.0
Yards	Meters	0.9144
	Pressure	
Dynes per cm^2	Pascals	0.1000
Grams per cm^3	Ounces per in^3	0.5780
Kilograms per cm^2	Pounds per in^2	14.223
Kilograms per cm^2	Pascals	98,066.5
Kilograms per m^2	Pascals	9.8066
Kilograms per m^2	Pounds per ft^2	0.2048
Kilograms per m^2	Pounds per yd^2	1.8433
Kilograms per m^3	Pounds per ft^3	0.06243
Ounces per in^3	Grams per cm^3	1.7300
Pounds per ft^3	Kilograms per cm^3	16.019
Pounds per ft^2	Kilograms per m^2	4.8824
Pounds per ft^2	Pascals	47.880
Pounds per in^2	Kilograms per cm^2	0.0703
Pounds per in^2	Pascals	6,894.76
Pounds per yd^2	Kilograms per m^2	0.5425
	Velocity	
Feet per minute	Meters per second	0.00508
Feet per second	Meters per second	0.3048
Inches per second	Meters per second	0.0254
Miles per hour	Meters per second	0.4470
	Volume	
Cubic centimeters	Cubic inches	0.06102
Cubic feet	Cubic inches	1,728.0
Cubic feet	Cubic meters	0.0283
Cubic feet	Cubic yards	0.0370
Cubic feet	Gallons	7.481
Cubic feet	Liters	28.32
Cubic feet	Quarts	29.9222
Cubic inches	Cubic centimeters	16.39
Cubic inches	Cubic feet	0.0005787
Cubic inches	Cubic meters	0.00001639

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U.S. Customary and Metric (SI) Measures and Conversions

Cubic inches	Liters	0.0164
Cubic inches	Gallons	0.004329
Cubic inches	Quarts	0.01732
Cubic meters	Cubic feet	35.31
Cubic meters	Cubic inches	61,023.
Cubic meters	Cubic yards	1.3087
Cubic yards	Cubic feet	27.0
Cubic yards	Cubic meters	0.7641
Gallons	Cubic feet	0.1337
Gallons	Cubic inches	231.0
Gallons	Cubic meters	0.003785
Gallons	Liters	3.785
Gallons	Quarts	4.0
Liters	Cubic feet	0.0351
Liters	Cubic inches	61.017
Liters	Gallons	0.2642
Liters	Pints	2.1133
Liters	Quarts	1.057
Liters	Cubic meters	0.0010
Pints	Cubic meters	0.004732
Pints	Liters	0.4732
Pints	Quarts	0.50
Quarts	Cubic feet	0.03342
Quarts	Cubic inches	57.75
Quarts	Cubic meters	0.0009464
Quarts	Gallons	0.25
Quarts	Liters	0.9464
Quarts	Pints	2.0
	Weight	
Grams	Kilograms	0.001
Grams	Ounces	0.03527
Grams	Pounds	0.002205
Kilograms	Ounces	35.274
Kilograms	Pounds	2.2046
Ounces	Grams	28.35
Ounces	Kilograms	0.02835
Ounces	Pounds	0.0625
Pounds	Grams	453.6
Pounds	Kilograms	0.4536
Pounds	Ounces	16.0

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3.2 Standard Conversion Table: Measures Are Found from the Table

Multiply:	By:	To obtain:
Atmospheres	76.0	Centimeters of mercury
Atmospheres	29.92	Inches of mercury
Atmospheres	33.90	Feet of water
Atmospheres	10,333	Kilograms per square meter
Atmospheres	14.70	Pounds per square inch
Atmospheres	1.058	Tons per square foot
Barrels—oil	42	Gallons—oil
British thermal units (Btu)	0.2520	Kilogram-calories
British thermal units	777.5	Foot pounds
British thermal units	3.927×10^{-4}	Horsepower-hours
British thermal units	107.5	Kilogram-meters
British thermal units	2.928×10^{-4}	Kilowatt-hours
Btu/min	12.96	Foot pounds per second
Btu/min	0.02356	Horsepower
Btu/min	0.01757	Kilowatts
Btu/min	17.57	Watts
Centares (centiares)	1	Square meters
Centigrams	0.01	Grams
Centiliters	0.01	Liters
Centimeters	0.3937	Inches
Centimeters	0.01	Meters
Centimeters	10	Millimeters
Centimeters of mercury	0.01316	Atmospheres
Centimeters of mercury	0.4461	Feet of water
Centimeters of mercury	136.0	Kilograms per square meter
Centimeters of mercury	27.85	Pounds per square foot
Centimeters of mercury	0.1934	Pounds per square inch
Centimeters per second	1.969	Feet per minute
Centimeters per second	0.03281	Feet per second
Centimeters per second	0.036	Kilometers per hour
Centimeters per second	0.6	Meters per minute
Centimeters per second	0.02237	Miles per hour
Centimeters per second	3.728×10^{-4}	Miles per minute
Centimeters per second per second	0.03281	Feet per second per second
Cubic centimeters	3.531×10^{-5}	Cubic feet
Cubic centimeters	6.102×10^{-2}	Cubic inches
Cubic centimeters	10^{-6}	Cubic meters
Cubic centimeters	1.308×10^{-6}	Cubic yards
Cubic centimeters	2.642×10^{-4}	Gallons
Cubic centimeters	10^{-3}	Liters

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U.S. Customary and Metric (SI) Measures and Conversions

Cubic centimeters	2.113×10^{-3}	Pints (liq.)
Cubic centimeters	1.057×10^{-3}	Quarts (liq.)
Cubic feet	2.832×10^{4}	Cubic centimeters
Cubic feet	1728	Cubic inches
Cubic feet	0.02832	Cubic meters
Cubic feet	0.03704	Cubic yards
Cubic feet	7.48052	Gallons
Cubic feet	28.32	Liters
Cubic feet	59.84	Pints (liq.)
Cubic feet	29.92	Quarts (liq.)
Cubic feet per minute	472.0	Cubic centimeters per second
Cubic feet per minute	0.1247	Gallons per second
Cubic feet per minute	0.4720	Liters per second
Cubic feet per minute	62.43	Pounds of water per minute
Cubic feet per second	0.646317	Million gallons per day
Cubic feet per second	448.831	Gallons per minute
Cubic inches	16.39	Cubic centimeters
Cubic inches	5.787×10^{-4}	Cubic feet
Cubic inches	4.329×10^{-3}	Gallons
Cubic inches	1.639×10^{-2}	Liters
Cubic inches	0.03463	Pints (liq.)
Cubic inches	0.01732	Quarts (liq.)
Cubic meters	10^{6}	Cubic centimeters
Cubic meters	35.31	Cubic feet
Cubic meters	61.023×10^{3}	Cubic inches
Cubic meters	1.308	Cubic yards
Cubic meters	264.2	Gallons
Cubic meters	10^{3}	Liters
Cubic meters	2113	Pints (liq.)
Cubic meters	1057	Quarts (liq.)
Cubic yards	7.646×10^{5}	Cubic centimeters
Cubic yards	27	Cubic feet
Cubic yards	46,656	Cubic inches
Cubic yards	0.7646	Cubic meters
Cubic yards	202.0	Gallons
Cubic yards	764.6	Liters
Cubic yards	1616	Pints (liq.)
Cubic yards	807.9	Quarts (liq.)
Cubic yards per minute	0.45	Cubic feet per second
Cubic yards per minute	3.367	Gallons per second
Cubic yards per minute	12.74	Liters per second
Decigrams	0.1	Grams
Deciliters	0.1	Liters
Decimeters	0.1	Meters
Degrees (angle)	60	Minutes
Degrees (angle)	0.01745	Radians

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Multiply:	By:	To obtain:
Degrees (angle)	3600	Seconds
Degrees per second	0.01745	Radians per second
Degrees per second	0.1667	Revolutions per minute
Degrees per second	0.002778	Revolutions per second
Drams	0.0625	Ounces
Drams	1.771845	Grams
Feet	30.48	Centimeters
Feet	12	Inches
Feet	0.3048	Meters
Feet	⅓	Yards
Feet of water	0.02950	Atmospheres
Feet per minute	0.5080	Centimeters per second
Feet per minute	0.01667	Feet per second
Feet per minute	0.01829	Kilometers per hour
Feet per minute	0.3048	Meters per minute
Feet per second	18.29	Meters per minute
Gallons	3785	Cubic centimeters
Gallons	0.1337	Cubic feet
Gallons	231	Cubic inches
Gallons	3.785×10^{-3}	Cubic meters
Gallons	4.95×10^{-3}	Cubic yards
Gallons	3.785	Liters
Gallons	8	Pints (liq.)
Gallons	4	Quarts (liq.)
Gallons—Imperial	1.20095	U.S. gallons
Gallons—U.S.	0.83267	Imperial gallons
Gallons water	8.3453	Pounds of water
Gallons per minute	2.228×10^{-3}	Cubic feet per second
Gallons per minute	0.06308	Liters per second
Gallons per minute	8.0208	Cubic feet per hour
Grams	980.7	Dynes
Grams	15.43	Grains
Grams	10^{-3}	Kilograms
Grams	10^{3}	Milligrams
Grams	0.03527	Ounces
Grams	0.03215	Ounces (troy)
Grams	2.205×10^{-3}	Pounds
Grams per centimeter	5.600×10^{-3}	Pounds per inch
Grams per cubic centimeter	62.43	Pounds per cubic foot
Grams per cubic centimeter	0.03613	Pounds per cubic inch
Grams per liter	0.062427	Pounds per cubic foot
Horsepower	42.44	Btu per minute
Horsepower	33,000	Foot pounds per minute
Horsepower	550	Foot pounds per second

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U.S. Customary and Metric (SI) Measures and Conversions

Horsepower	1.014	Horsepower (metric)
Horsepower	10.70	Kilogram-calories per minute
Horsepower	0.7457	Kilowatts
Horsepower	745.7	Watts
Horsepower (boiler)	33,479	Btu per hour
Horsepower (boiler)	9803	Kilowatts
Horsepower-hours	2547	British thermal units
Horsepower-hours	1.98×10^{6}	Foot pounds
Horsepower-hours	641.7	Kilogram-calories
Horsepower-hours	2.737×10^{5}	Kilogram-meters
Horsepower-hours	0.7457	Kilowatthours
Inches	2.540	Centimeters
Inches of mercury	0.03342	Atmospheres
Inches of mercury	1.133	Feet of water
Inches of mercury	345.3	Kilograms per square meter
Inches of mercury	70.73	Pounds per square foot
Inches of mercury	0.4912	Pounds per square inch
Inches of water	0.002458	Atmospheres
Inches of water	0.07355	Inches of mercury
Inches of water	25.40	Kilograms per square meter
Inches of water	0.5781	Ounces per square inch
Inches of water	5.202	Pounds per square foot
Inches of water	0.03613	Pounds per square inch
Kilograms	980,665	Dynes
Kilograms	2.205	Pounds
Kilograms	1.102×10^{-3}	Tons (short)
Kilograms	10^{3}	Grams
Kilogram-calories	3.968	British thermal units
Kilogram-calories	3086	Foot pounds
Kilogram-calories	1.558×10^{-3}	Horsepower-hours
Kilogram-calories	1.162×10^{-3}	Kilowatthours
Kilogram-calories per minute	51.43	Foot pounds per second
Kilogram-calories per minute	0.09351	Horsepower
Kilogram-calories per minute	0.06972	Kilowatts
Kilograms per meter	0.6720	Pounds per foot
Kilograms per square meter	9.678×10^{-5}	Atmospheres
Kilograms per square meter	3.281×10^{-3}	Feet of water
Kilograms per square meter	2.896×10^{-3}	Inches of mercury
Kilograms per square meter	0.2048	Pounds per square foot

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Multiply:	By:	To obtain:
Kilograms per square meter	1.422×10^{-3}	Pounds per square inch
Kilograms per square millimeter	10^{6}	Kilograms per square meter
Kiloliters	10^{3}	Liters
Kilometers	10^{5}	Centimeters
Kilometers	3281	Feet
Kilometers	10^{3}	Meters
Kilometers	0.6214	Miles
Kilometers	1094	Yards
Kilometers per hour	27.78	Centimeters per second
Kilometers per hour	54.68	Feet per minute
Kilometers per hour	0.9113	Feet per second
Kilometers per hour	0.5396	Knots
Kilometers per hour	16.67	Meters per minute
Kilometers per hour	0.6214	Miles per hour
Kilograms per hour per second	27.78	Centimeters per second per second
Kilograms per hour per second	0.9113	Feet per second per second
Kilograms per hour per second	0.2778	Meters per second per second
Kilowatts	56.92	Btu per minute
Kilowatts	4.425×10^{4}	Foot pounds per minute
Kilowatts	737.6	Foot pounds per second
Kilowatts	1.341	Horsepower
Kilowatts	14.34	Kilogram-calories per minute
Kilowatts	10^{3}	Watts
Kilowatthours	3415	British thermal units
Kilowatthours	2.655×10^{6}	Foot pounds
Kilowatthours	1.341	Horsepower-hours
Kilowatthours	860.5	Kilogram-calories
Kilowatthours	3.671×10^{5}	Kilogram-meters
Liters	10^{3}	Cubic centimeters
Liters	0.03531	Cubic feet
Liters	61.02	Cubic inches
Liters	10^{3}	Cubic meters
Liters	1.308×10^{-3}	Cubic yards
Liters	0.2642	Gallons
Liters	2.113	Pints (liq.)
Liters	1.057	Quarts (liq.)
Liters per minute	5.886×10^{-4}	Cubic feet per second
Liters per minute	4.403×10^{-3}	Gallons per second
Meters	100	Centimeters
Meters	3.281	Feet
Meters	39.37	Inches
Meters	10^{3}	Millimeters

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U.S. Customary and Metric (SI) Measures and Conversions

Meters	1.094	Yards
Meters per minute	1.667	Centimeters per second
Meters per minute	3.281	Feet per minute
Meters per minute	0.05468	Feet per second
Meters per second	196.8	Feet per minute
Meters per second	3.281	Feet per second
Microns	10^{-6}	Meters
Milligrams	10^{-3}	Grams
Milliliters	10^{-3}	Liters
Millimeters	0.1	Centimeters
Millimeters	0.03937	Inches
Million gallons per day	1.54723	Cubic feet per second
Minutes (angle)	2.909×10^{-4}	Radians
Ounces	16	Drams
Ounces	437.5	Grains
Ounces	0.0625	Pounds
Ounces	28.349527	Grams
Ounces	0.9115	Ounces (troy)
Ounces	2.790×10^{-5}	Tons (long)
Ounces	2.835×10^{-5}	Tons (metric)
Ounces (troy)	480	Grains
Ounces (troy)	20	Pennyweights (troy)
Ounces (troy)	0.08333	Pounds (troy)
Ounces (troy)	31.103481	Grams
Ounces (troy)	1.09714	Ounces (avoir.)
Ounces (fluid)	1.805	Cubic inches
Ounces (fluid)	0.02957	Liters
Ounces per square inch	0.0625	Pounds per square inch
Pennyweights (troy)	24	Grains
Pennyweights (troy)	1.55517	Grams
Pennyweights (troy)	0.05	Ounces (troy)
Pennyweights (troy)	4.1667×10^{-3}	Pounds (troy)
Pounds	16	Ounces
Pounds	256	Drams
Pounds	7000	Grains
Pounds	453.5924	Grams
Pounds	1.21528	Pounds (troy)
Pounds	14.5833	Ounces (troy)
Pounds (troy)	5760	Grains
Pounds (troy)	240	Pennyweights (troy)
Pounds (troy)	12	Ounces (troy)
Pounds (troy)	373.24177	Grams
Pounds (troy)	0.822857	Pounds (avoir.)
Pounds (troy)	13.1657	Ounces (avoir.)
Pounds of water	0.01602	Cubic feet
Pounds of water	27.68	Cubic inches
Pounds of water	0.1198	Gallons
Pounds of water per minute	2.670×10^{-4}	Cubic feet per second

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Multiply:	By:	To obtain:
Pounds per cubic foot	0.01602	Grams per cubic centimeter
Pounds per cubic foot	16.02	Kilograms per cubic meter
Pounds per cubic foot	5.787×10^{-4}	Pounds per cubic inch
Pounds per cubic inch	27.68	Grams per cubic centimeter
Pounds per cubic inch	2.768×10^{4}	Kilograms per cubic meter
Pounds per cubic inch	1728	Pounds per cubic foot
Pounds per foot	1.488	Kilograms per meter
Pounds per inch	178.6	Grams per centimeter
Pounds per square foot	0.01602	Feet of water
Pounds per square foot	4.883	Kilograms per square meter
Pounds per square foot	6.945×10^{-3}	Pounds per square inch
Pounds per square inch	0.06804	Atmospheres
Pounds per square inch	2.307	Feet of water
Pounds per square inch	2.036	Inches of mercury
Pounds per square inch	703.1	Kilograms per square meter
Quarts (dry)	67.20	Cubic inches
Quarts (liq.)	57.75	Cubic inches
Radians	57.30	Degrees
Radians	3438	Minutes
Radians per second	57.30	Degrees per second
Radians	0.1592	Revolutions per second
Radians per second	9.549	Revolutions per minute
Radians per second	573.0	Revolutions per minute
Radians per second	0.1592	Revolutions per second
Revolutions	360	Degrees
Revolutions	6.283	Radians
Revolutions per minute	6	Degrees per second
Revolutions per minute	0.1047	Radians per second
Revolutions per minute	0.01667	Revolutions per second
Revolutions per minute	1.745×10^{-3}	Radians per second
Revolutions per minute	2.778×10^{-4}	Revolutions per second
Revolutions per second	360	Degrees per second
Revolutions per second	6.283	Radians per second
Revolutions per second	60	Revolutions per minute
Revolutions per second	6.283	Radians per second
Revolutions per second	3600	Revolutions per minute
Seconds (angle)	4.848×10^{-6}	Radians
Temperature (°C) + 273	1	Abs. temp. (°C)
Temperature (°C) + 17.78	1.8	Temp. (°F)
Temperature (°F) + 460	1	Abs. temp. (°F)
Temperature (°F) – 32	5/9	Temp. (°C)
Watts	0.05692	Btu per minute

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U.S. Customary and Metric (SI) Measures and Conversions

Watts	44.26	Foot pounds per minute
Watts	0.7376	Foot pounds per second
Watts	1.341×10^{-3}	Horsepower
Watts	0.01434	Kilogram-calories per minute
Watts	10^{-3}	Kilowatts
Watthours	3.415	British thermal units
Watthours	2655	Foot pounds
Watthours	1.341×10^{-3}	Horsepower-hours
Watthours	0.8605	Kilogram-calories
Watthours	367.1	Kilogram-meters
Watthours	10^{-3}	Kilowatthours
Yards	91.44	Centimeters
Yards	3	Feet
Yards	36	Inches
Yards	0.9144	Meters

3.3 Temperature Systems and Conversions

There are four common temperature systems used in engineering and design calculations: (°F) Fahrenheit, (°C) Celsius (formerly centigrade), (°K) Kelvin, and (°R) Rankine. The conversion equation for Celsius to Fahrenheit or Fahrenheit to Celsius is

$$\frac{5}{9} = \frac{°C}{°F - 32}$$

This exact relational equation is all that you need to convert from either system. Enter the known temperature, and solve the equation for the unknown value.

Example: You wish to convert 66°C to Fahrenheit.

$$\frac{5}{9} = \frac{66}{°F - 32}$$

$$5°F - 160 = 594$$

$$°F = 150.8$$

The other two systems, Kelvin and Rankine, are converted as described here. The Kelvin and Celsius scales are related by the equation

$$K = 273.18 + °C$$

Thus 0°C = 273.18 K. Absolute zero is equal to –273.18°C.

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Example: A temperature of $-75°C = 273.18 + (-75°C) = 198.18$ K.

The Rankine and Fahrenheit scales are related by the equation

$$°R = 459.69 + °F$$

Thus $0°F = 459.69°R$. Absolute zero is equal to $-459.69°F$.

Example: A temperature of $75°F = 459.69 + (+75°F) = 534.69°R$.

3.4 Small Weight Equivalents: U.S. Customary (Grains and Ounces) versus Metric (Grams)

1 gram	= 15.43 grains
1 gram	= 15,430 milligrains
1 gram	= 15,430,000 micrograins
1 pound	= 7,000 grains
1 ounce	= 437.5 grains
1 ounce	= 28.35 grams
1 grain	= 0.0648 grams
1 grain	= 64.8 milligrams
0.1 grain	= 0.00648 grams
0.1 grain	= 6.48 milligrams
1 micrograin	= 0.0000000648 grams
1 micrograin	= 0.0000648 milligrams
1000 micrograins	= 0.0000648 grams
1000 micrograins	= 0.0648 milligrams
1 grain	= 0.002286 ounces
1 ounce	= 437.5 grains
10 grains	= 0.02286 ounces or 0.648 grams
100 grains	= 0.2286 ounces or 6.48 grams

Example: To obtain the weight in grams, multiply the weight in grains by 0.0648, or divide the weight in grains by 15.43.

Example: To obtain the weight in grains, multiply the weight in grams by 15.43, or divide the weight in grams by 0.0648.

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Chapter

4

Materials: Physical Properties, Characteristics, and Uses

Materials, including metals, alloys, plastics, and other composite compounds, are of prime importance to the mechanical designer, tool designer, machinist, and metalworker. The most important characteristics of materials to those who design and manufacture parts are the physical and chemical properties and the various uses to which the materials may be applied. This chapter discusses a great number of metals, alloys, plastics, and compounds, including elastomers. Included are composition, physical properties, hardness, heat-treatment temperatures, and other characteristics useful for design and metalworking practices.

In design and metalworking practices, sometimes a material defect or failure occurs for unknown reasons. With the information provided in this chapter and in other appropriate American Society for Testing and Materials (ASTM), Society of Automotive Engineers (SAE), American Iron and Steel Institute (AISI), and American Gear Manufacturers Association (AGMA) standards, you may decide to have the material analyzed at a metallurgical and chemical laboratory to check the properties and compositions, or you may have the material checked mechanically at your company to determine if it meets the requirements of the material standards listed herein.

When producing the engineering drawings or specifications for a particular part, the appropriate American standard material designation or military/federal specification always must be indicated

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on the drawings or specifications. For example, if you are preparing a drawing for a mechanical spring, and you wish to use music wire in its construction, you must indicate on the drawing that the material is to meet ASTM A-228 or appropriate SAE specifications. You also may request a certified material analysis data sheet from the supplier of the material, whether it comes from a mill, a foundry, a forge, or a materials processing plant. It is the responsibility of material suppliers to provide design engineers and purchasing departments with these analysis sheets when so directed, which is the usual procedure.

Chapter 7 of this *Handbook* lists the machining characteristics and machine tool cutting and drilling speeds for many common and popular steels, alloys, other metals, plastics, and composites. In this chapter you also will find master cross-reference tables of all current hardness scales or systems such as Rockwell, Brinell, and Vickers. With these tables, you will be able to convert the hardness numbers for all the common and currently used hardness measurement systems relative to each other.

Materials specifications and characteristics or properties tables throughout this and other chapters of this *Handbook* are extracted from the latest standards of the ASTM, SAE, and AGMA.

There are a tremendous number of different engineering materials for which the ASTM and SAE have listings: metallic, plastic, and composite. Steels alone account for hundreds of different alloys for wrought products, castings, and forgings. Although these alloys are listed and have specifications for composition and physical properties, they may not be readily available, except as special order "mill run" quantities. A typical example would be austenitic stainless steel sheet in light gauges, cold-rolled to three-quarters hard, spring temper. This material is listed in the various 300 series stainless steels but may only be available from stock in 301 grade, three-quarters hard, spring temper. If you require 304 grade in your design application, it may be available only in mill-run quantities of a minimum of 500 to 2000 lb per single order.

As a general rule, during the early design stages of a particular part, alternate materials must be investigated. Owing to limited availability of your chosen material, you may be forced to use another material that is stocked by the material vendors. When your anticipated material quantities are large, you then will have control of the material type as well as its physical size and special characteristics, such as finish, temper, and gauge. For example, some of the larger companies that order hundreds of tons of hot-rolled sheet steel per year may specify to the mill that they want to run light on

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the minus side of a particular gauge. The tolerance on hot-rolled sheet steel is such that when it is run on the minus side of the gauge limits, many thousands of pounds of steel can be saved. The same is true for wrought-copper products such as bus bars and copper sheet, where the savings may be even more advantageous.

The list of steel alloys is so large that some authorities and regulating organizations have contemplated restricting the material standards to controlled listings, wherein redundant materials are eliminated. The large listings of alloys, plastics, and composites create a stocking problem for distributors of mill products, plastics, and composite materials.

For designers, machinists, tool makers, and metalworkers employed at small to medium-sized companies, a good approach to the aforementioned materials problems is to obtain the stock materials catalogs available from the large distributors and manufacturers such as Ryerson, Vincent, Atlantic, Alcoa, Reynolds, Bethlehem Steel, U.S. Steel, Anaconda, General Electric, Dupont, Monsanto, and others. The design and fabrication data for a great number of materials are listed in this and other chapters of this *Handbook*, together with typical uses and applications for these materials.

4.1 Steels

This section lists carbon and alloy steels, as well as the stainless steels, in their wrought form, that is to say, in the hot-rolled, cold rolled, or cold-drawn forms. The usual shapes are sheets, plates, bars or strips, rounds, hexagons, tube, pipe, and structural configurations (beams, angles, channels, tees, square and rectangular tubes, and zees). Cast irons and steels and other casting materials are listed in Chap. 12.

When carbon is added to iron in small quantities, carbon steel is produced. Besides carbon, a number of metallic elements can be added to iron to give the characteristics inherent in the various types of steels. The usual alloying elements are

- Aluminum, which controls grain size in the steel
- Boron, which improves hardenability
- Chromium, which increases response to heat treatment as well as toughness (Chromium is used in stainless steels alone or with nickel.)
- Columbium, which is used in 18-8 stainless steels and welding electrodes

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- Copper, which controls atmospheric corrosion and increases yield strengths
- Lead, which greatly improves machinability
- Manganese, which imparts strength and response to heat treatment
- Molybdenum, which increases depth of hardness and toughness
- Nickel, which increases strength and toughness but is not effective in improving hardenability
- Phosphorus, which is present in all steels and increases yield strength
- Silicon, which improves tensile strength and can improve hardenability
- Sulfur, which improves machinability but is detrimental to hot-forming properties
- Tellurium, which improves machinability in leaded steels
- Titanium, which is added to 18-8 stainless steels to prevent carbide precipitation
- Tungsten, which is used in good tool steels, making a fine-grain structure when used in small amounts (When used in amounts from 17 to 20 percent, it produces a high-speed steel that retains hardness at high temperatures.)
- Vanadium, which is used to improve the shock strength of steels and retards grain growth even after hardening from high temperatures

4.1.1 Glossary of steel terms

Age hardening A process of aging that increases hardness and strength. Age hardening usually follows rapid cooling or cold working.

Annealing A process involving heat and cooling, usually applied to induce softening.

Austenite A term designating a metallurgical phase of steels, i.e., austenitic stainless steel.

Carburizing To introduce carbon while the steel is molten or while it is in the solid state by heating it in contact with carbonaceous material below its melting point.

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Case hardening A process of hardening a ferrous alloy so that the case, or surface layer, is much harder than the interior of the part. The typical case-hardening processes are carburizing and quenching, cyaniding, carbonitriding, nitriding, induction hardening, and flame hardening. Cases of Rockwell C 55 to 60 are readily obtained in medium- to high-carbon steels.

Ductility The property of a material that allows it to be drawn out of shape before fracturing by stress.

Elastic limit The maximum stress a material is capable of sustaining without a permanent set or deformation.

Fatigue The tendency for a metal to break after repeated or cyclic loadings that are below the ultimate tensile strength. Also known as *fatigue-endurance limit.*

Flame hardening A process of hardening a ferrous alloy by heating it above the transformation range by means of a flame and then cooling as required.

Hardenability The property of a ferrous alloy that determines the depth and distribution of hardness induced by quenching.

Induction hardening A process of hardening a ferrous alloy by heating it above the transformation range by means of electrical induction and then cooling as required.

Killed steel Steel that is deoxidized with silicon or aluminum in order to reduce the oxygen content so that no reaction occurs between carbon and oxygen during solidification.

Martensite An unstable constituent in quenched steel formed without diffusion only during cooling below a certain temperature. Martensite is the hardest of the transformation products of austenite.

Nitriding A process of case hardening in which a ferrous alloy, usually of special composition, is heated in an atmosphere of ammonia or in direct contact with a nitrogenous material to produce surface hardening by absorbing nitrogen without quenching.

Normalizing Heating a steel part of heavy section to a temperature 100°F above the critical range and then cooling in still air.

Pickeling Chemical or electrochemical removal of surface scale and oxides.

Quench hardening Heating a steel within or above the transformation range and cooling at a rate faster than the critical rate

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to increase the hardness substantially. Usually involves the formation of martensite.

Solution heat treatment A process in which an alloy is heated to a suitable temperature, held at this temperature long enough for certain constituents to enter into solid solution, and then cooled rapidly to hold the constituent in solution. The metal is left in a supersaturated state that is unstable and subsequently may exhibit age hardening.

Spheroidizing Any process of heating and cooling that produces a round or globular form of carbide in steels.

Strain hardening An increase in hardness and strength caused by plastic deformation at temperatures lower than the recrystallization range.

Stress relieving A process of reducing residual stresses in a metal part by heating the part to a suitable temperature and holding this temperature for a sufficient time. This process is applied to relieve stresses induced by casting, quenching, normalizing, machining, cold working (i.e., springs), or welding.

Temper A condition produced in a metal or alloy by mechanical or thermal treatment and having characteristic structure and mechanical properties. In addition to the annealed temper, conditions produced by thermal treatment are the solution heat-treated temper and the heat-treated and artificially aged temper.

Yield strength The stress at which a material exhibits a specified limited deviation from proportionality of stress to strain. In most steels, there is a proportionality between the amount of stress that produces a certain amount of strain. This phenomenon is known as *Hooke's law.* When a material passes its yield point, a lesser amount of stress produces a greater amount of strain until the ultimate strength point is reached, where the material breaks.

4.1.2 Carbon, alloy, stainless steel, and tool and die steels: Physical properties, compositions, heat treatment, and uses

Tables 4.1 through 4.20 contain the numbering system for identification of the various types of steels given in the SAE and Unified Numbering System (UNS) designations. Figure 4.1 shows properties and heat treatments for carbon, alloy, and stainless steel. Table 4.21 is an approximate equivalent hardness number table for Brinell hardness numbers for steel, with cross-references to other hardness

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designation systems. Table 4.22 is an approximate equivalent hardness number table for Rockwell C hardness numbers for steel, with cross-references to other hardness designation systems.

Typical uses for the various steels. Following is a listing of the popular and readily available steels that are usually stocked by suppliers and which have vast applications in industry. Tables 4.1 through 4.20 show the physical properties and heat-treatment processes for a great number of American standard steels. The following list of applications will prove useful to many designers and mechanical engineers, as well as to machinists, tool engineers, tool and die makers, and other metalworkers throughout industry. The following list is not all-inclusive but rather is indicative of the much-used and readily available types of carbon, alloy, and stainless steels.

(Text continued on page 150.)

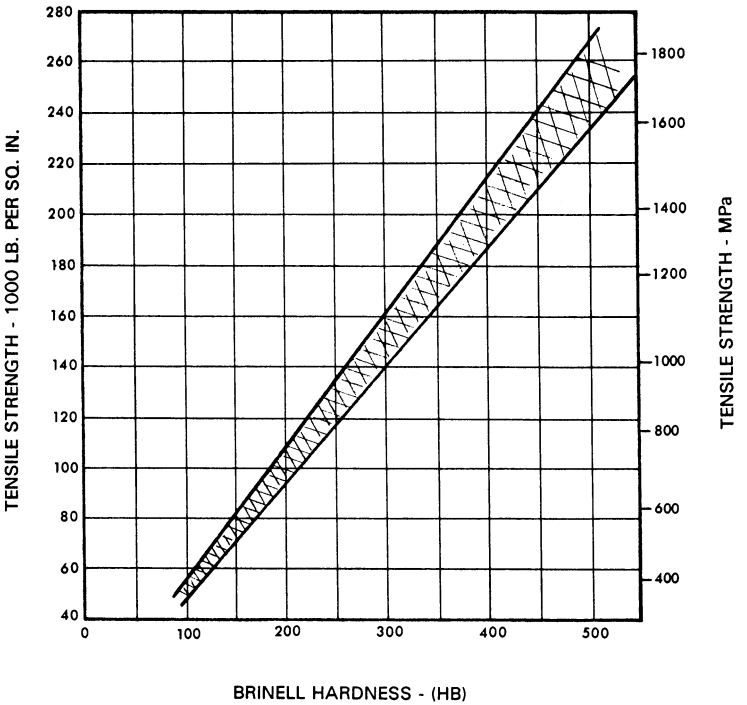

Figure 4.1 Brinell hardness numbers indicating approximate tensile strengths of steels.

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TABLE 4.1 Designation System for Steels (SAE and UNS)

Numerals and digits		Type of identifying elements	Refer to SAE Standard or Information Report—JXXX for composition limits
UNS	SAE		
		Carbon Steels	
G10XX0	10XX*	Nonresulfurized, manganese 1.00% maximum	403 and 1249
G11XX0	11XX	Resulfurized	403 and 1249
G12XX0	12XX	Rephosphorized and resulfurized	403
		Alloy Steels	
G13XX0	13XX	Manganese steels	404 and 1249
G23XX0	23XX	Nickel steels	1249
G25XX0	25XX	Nickel steels	1249
G31XX0	31XX	Nickel-chromium steels	1249
G32XX0	32XX	Nickel-chromium steels	1249
G33XX0	33XX	Nickel-chromium steels	1249
G34XX0	34XX	Nickel-chromium steels	1249
G40XX0	40XX	Molybdenum steels	404 and 1249
G41XX0	41XX	Chromium-molybdenum steels	404 and 1249
G43XX0	43XX	Nickel-chromium-molybdenum steels	404 and 1249
G44XX0	44XX	Molybdenum steels	404 and 1249
G46XX0	46XX	Nickel-molybdenum steels	404 and 1249
G47XX0	47XX	Nickel-chromium-molybdenum steels	404
G48XX0	48XX	Nickel-molybdenum steels	404 and 1249
G50XX0	50XX	Chromium steels	404 and 1249
G51XX0	51XX	Chromium steels	404 and 1249
G50XX6	50XXX	Chromium steels	404
G51XX6	51XXX	Chromium steels	404

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G52XX6	52XXX	Chromium steels	404
G61XX0	61XX	Chromium-vanadium steels	404 and 1249
G71XX0	71XXX	Tungsten-chromium steels	1249
G72XX0	72XX	Tungsten-chromium steels	1249
G81XX0	81XX	Nickel-chromium-molybdenum steels	404
G86XX0	86XX	Nickel-chromium-molybdenum steels	404 and 1249
G87XX0	87XX	Nickel-chromium-molybdenum steels	404 and 1249
G88XX0	88XX	Nickel-chromium-molybdenum steels	404
G92XX0	92XX	Silicon-manganese steels	404 and 1249
G93XX0	93XX	Nickel-chromium-molybdenum steels	404 and 1249
G94XX0	94XX	Nickel-chromium-molybdenum steels	404 and 1249
G97XX0	97XX	Nickel-chromium-molybdenum steels	1249
G98XX0	98XX	Nickel-chromium-molybdenum steels	1249
		Carbon and Alloy Steels	
GXXXX1	XXBXX	B denotes boron steels	403 and 404
GXXXX4	XXLXX	L denotes leaded steels	403 and 404
		Stainless Steels	
S2XXXX	302XX	Chromium-nickel steels	405
S3XXXX	303XX	Chromium-nickel steels	405
S4XXXX	514XX	Chromium steels	405
S5XXXX	515XX	Chromium steels	405
		Experimental Steels	
None	EX—	SAE experimental steels	1081

* SAE J403 describes UNS G 15XX0 and SAE 15XX as applicable only to semifinished products for forging, for hot-rolled and cold-finished bars, for wire rods, and for seamless tubing.

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TABLE 4.2 Mechanical Requirements-Stainless Steels

Type	Condition	Finish	Diameter or thickness, in (mm)	Tensile strength, min ksi	Tensile strength, min MPa	Yield strength,[a] min ksi	Yield strength,[a] min MPa	Elongation in 2 in or 50 mm,[b] min, %	Reduction of area,[c] min, %	Brinell hardness, max
			Austenitic Grades							
201, 202	A	Hot finished or cold finished	All	75	515	40	275	40	45	—
S20161	A	Hot finished or cold finished	All	125	860	50	345	40	40	255
205	A	Hot finished or cold finished	All	100	690	60	414	40	50	—
XM-19	A	Hot finished or cold finished	All	100	690	55	380	35	55	—
XM-19	As hot rolled	Hot finished or cold finished	Up to 2 (50.8), incl	135	930	105	725	20	50	—
			Over 2 to 3 (50.8 to 76.2), incl	115	795	75	515	25	50	—
			Over 3 to 8 (76.2 to 203.2), incl	100	690	60	415	30	50	—
S21800	A	Hot finished or cold finished	All	95	655	50	345	35	55	241
XM-10, XM-11	A	Hot finished or cold finished	All	90	620	50	345	45	60	—
XM-29	A	Hot finished or cold finished	All	100	690	55	380	30	50	—
XM-28	A	Hot finished or cold finished	All	100	690	55	380	30	50	—
S 28200	A	Hot finished or cold finished	All	110	760	60	410	35	55	—
302, 302B, 304, 304LN, 305, 308, 309, 309S, 309CB, 310, 310S, 310CB, 314, 316, 316LN, 316CB, 316TI, 317, 321, 347, 348	A	Hot finished	All	75[e]	515	30[e]	205	40[g]	50	—
		Cold finished	Up to ½ (12.70) incl	90	620	45	310	30	40	—
			Over ½ (12.70)	75[e]	515	30[e]	205	30	40	—
304L, 316L	A	Hot finished	All	70	480	25	170	40[g]	50	—
		Cold finished	Up to ½ (12.70) incl	90	620	45	310	30	40	—

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			Over ½ (12.70)	70	480	25	170	30	40	—
304N, 316N	A	Hot finished or cold finished	All	80	550	35	240	30	—	—
202, 302, 304, 304N, 316, 316N	B	Cold finished	Up to ¾ (19.05) incl	125	860	100	690	12	35	—
			Over ¾ (19.05) to 1 (25.40)	115	795	80	550	15	35	—
			Over 1 (25.40) to 1¼ (31.75)	105	725	65	450	20	35	—
			Over 1¼ (31.75) to 1½ (38.10)	100	690	50	345	24	45	—
			Over 1½ (38.10) to 1¾ (44.45)	95	655	45	310	28	45	—
304, 304N, 316, 316N	S	Cold finished	Up to 2 (50.8) incl	95	650	75	515	25	40	—
			Over 2 to 2½ (50.8 to 63.5) incl	90	620	65	450	30	40	—
			Over 2½ to 3 (63.5 to 76.2) incl	80	550	55	380	30	40	—
XM-21, S 30454, S 31654	A	Hot finished or cold finished	All	90	620	50	345	30	50	—
XM-21, S 30454 S 31654	B	Cold finished	Up to 1 (25.40) incl	145	1000	125	860	15	45	—
			Over 1 (25.40) to 1¼ (31.75)	135	930	115	795	16	45	—
			Over 1¼ (31.75) to 1½ (38.10)	135	895	105	725	17	45	—
			Over 1½ (38.10) to 1¾ (44.45)	125	860	100	690	18	45	—
XM-7	A	Hot finished or cold finished	All	70	480	25	170	40	50	—
S 30815	A	Hot finished or cold finished	All	87	600	45	310	40	50	—
S 31254	A	Hot finished or cold finished	All	95	650	44	300	35	50	—
S 31725	A	Hot finished or cold finished	All	75	515	30	205	40	—	—
S 31726	A	Hot finished or cold finished	All	80	550	35	240	40	—	—
			Austenitic-Ferritic Grades							
XM-26	A	Hot finished or cold finished	All	90	620	65	450	20	55	—
S 31803	A	Hot finished	All	90	620	65	448	25	—	290
		Cold finished	All	90	620	65	448	25	—	290

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TABLE 4.2 Mechanical Requirements-Stainless Steels (*Continued*)

Type	Condition	Finish	Diameter or thickness, in (mm)	Tensile strength, min		Yield strength,[a] min		Elongation in 2 in or 50 mm,[b] min, %	Reduction of area,[c] min, %	Brinell hardness, max
				ksi	MPa	ksi	MPa			
			Ferritic Grades							
405[f]	A	Hot finished	All	—	—	—	—	—	—	207
		Cold finished	All	—	—	—	—	—	—	217
429	A	Hot finished	All	70	480	40	275	20	45	—
		Cold finished	All	70	480	40	275	16	45	—
430	A	Hot finished or cold finished	All	60	415	30	207	20	45	—
S 44400	A	Hot finished	All	60	415	45	310	20	45	217
		Cold finished	All	60	415	45	310	16	45	217
446, XM-27	A	Hot finished	All	65	450	40	275	20	45	219
		Cold finished	All	65	450	40	275	16	45	219
S 44700	A	Hot finished	All	70	480	55	380	20	40	—
		Cold finished	All	75	520	60	415	15	30	—
S 44800	A	Hot finished	All	70	480	55	380	20	40	—
		Cold finished	All	75	520	60	415	15	30	—
			Martensitic Grades							
403, 410	A	Hot finished	All	70	480	40	275	20	45	—
		Cold finished	All	70	480	40	275	16	45	—
403, 410	T	Hot finished	All	100	690	80	550	15	45	—
		Cold finished	All	100	690	80	550	12	40	—
XM-30	T	Hot finished	All	125	860	100	690	13	45	302
		Cold finished	All	125	860	100	690	12	35	—
414	T	Hot finished or cold finished	All	115	790	90	620	15	45	—
403, 410	H	Hot finished	All	120	830	90	620	12	40	—
		Cold finished	All (rounds only)	120	830	90	620	12	40	—
XM-30	A	Hot finished	All	70	480	40	275	13	45	235
		Cold finished	All	70	480	40	275	12	35	—

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414	A	Hot finished or cold finished	All	—	—	—	—	—	—	298
S 41500	T	Hot finished or cold finished	All	115	795	90	620	15	45	295
420	A	Hot finished	All	—	—	—	—	—	—	241
		Cold finished	All	—	—	—	—	—	—	255
S 42010	A	Hot finished or cold finished		—	—	—	—	—	—	235
		Cold finished	All	—	—	—	—	—	—	255
431	A	Hot finished or cold finished	All	—	—	—	—	—	—	285
440A, 440B, and 440C	A	Hot finished	All	—	—	—	—	—	—	269
		Cold finished	All	—	—	—	—	—	—	285
9 (S 50400)	A	Hot finished or cold finished	All	60	415	30	207	30	45	179
	T	Hot finished or cold finished	All	100	690	80	550	14	35	241

[a] Yield strength shall be determined by the 0.2% offset method in accordance with Test Methods and Definitions A 370. An alternative method of determining yield strength may be used based on a total extension under load of 0.5%.

[b] For some specific products, it may not be practicable to use a 2-in or 50-mm gage length. The use of subsize test specimens, when necessary, is permissible in accordance with Test Methods and Definitions A 370.

[c] Reduction of area does not apply on flat bars 3/16 in (4.76 mm) and under in thickness as this determination is not generally made in this product size.

[d] Or equivalent Rockwell hardness.

[e] For extruded shapes of all Cr-Ni grades of condition A, the yield strength shall be 25 ksi (170 MPa) min and tensile strength shall be 70 ksi (480 MPa) min.

[f] Material shall be capable of being heat treated to a maximum Brinell hardness of 250 when oil quenched from 1750°F (953°C).

[g] For shapes having section thickness of 1/4 in (6.5 mm) or less, 30% min. elongation is acceptable.

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TABLE 4.3 Response to Heat Treatment

Type[a]	Heat treatment temperature °F (°C), min	Quenchant	Hardness HRC, min
403	1750 (955)	Air	35
410	1750 (955)	Air	35
414	1750 (955)	Oil	42
420	1825 (995)	Air	50
S42010	1850 (1010)	Oil	48
431	1875 (1020)	Oil	40
440A	1875 (1020)	Air	55
440B	1875 (1020)	Oil	56
440C	1875 (1020)	Air	58

[a] Samples for testing shall be in the form of a section not exceeding ¾ in (9.50 mm) in thickness.

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TABLE 4.4 Tensile Property Requirements[a]

Annealed

Type	UNS designation	Tensile strength, min psi	Tensile strength, min MPa	Yield strength, min psi	Yield strength, min MPa	Elongation in 2 in or 50 mm, min, %	Hardness, max Brinell	Hardness, max Rockwell B
201-1[b]	S20100 Class 1	95 000	655	38 000	260	40	217	95
201-2	S20100 Class 2	95 000	655	45 000	310	40	255	100
	S20200	90 000	620	38 000	260	40	—	—
205	S20500	115 000	790	65 000	450	40	255	100
301	S30100	90 000	620	30 000	205	40	217	95
302	S30200	75 000	515	30 000	205	40	201	92
304	S30400	75 000	515	30 000	205	40	201	92
304L	S30403	70 000	485	25 000	170	40	183	88
304N	S30451	80 000	550	35 000	240	40	217	95
304LN	—	80 000	550	35 000	240	40	217	95
316	S31600	75 000	515	30 000	205	40	217	95
316L	S31603	70 000	485	25 000	170	40	217	95
316N	S31651	80 000	550	35 000	240	40	217	95
	S21904							
	Sheet, strip	100 000	690	60 000	415	40	—	—
	Plate	90 000	620	50 000	345	45	—	—
	S21460	105 000	725	55 000	380	40	—	—

1/16 Hard[c]

Type	UNS designation	Tensile strength, min psi	Tensile strength, min MPa	Yield strength, min psi	Yield strength, min MPa	Elongation in 2 in or 50 mm, min, % <0.015 in	Elongation in 2 in or 50 mm, min, % ≥0.015 to ≤0.030 in	Elongation in 2 in or 50 mm, min, % >0.030 in
201	S20100 PSS[d]	95 000	655	45 000	310	40	40	40
	FB[e]	75 000	515	40 000	275	—	—	40
205	S20500	115 000	790	65 000	450	40	40	40
301	S30100	90 000	620	45 000	310	40	40	40
302	S30200 PSS	85 000	585	45 000	310	40	40	40
	FB	90 000	620	45 000	310	—	—	40
304	S30400 PSS	80 000	550	45 000	310	35	35	35
	FB	90 000	620	45 000	310	—	—	40
304L	S30403	80 000	550	45 000	310	40	40	40
304N	S30451	90 000	620	45 000	310	40	40	40
304LN	—	90 000	620	45 000	310	40	40	40
316	S31600 PSS	85 000	585	45 000	310	35	35	35
	FB	90 000	620	45 000	310	—	—	40
316L	S31603	85 000	585	45 000	310	35	35	35
316N	S31651	90 000	620	45 000	310	35	35	35

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TABLE 4.4 Tensile Property Requirements[a] (*Continued*)

⅛ Hard[c]

Type	UNS designation	Tensile strength, min psi	Tensile strength, min MPa	Yield strength, min psi	Yield strength, min MPa	Elongation in 2 in or 50 mm, min, % <0.015 in	Elongation in 2 in or 50 mm, min, % ≥0.015 to ≤0.030 in	Elongation in 2 in or 50 mm, min, % >0.030 in
201	S20100	100 000	690	55 000	380	45	45	45
205	S20500	115 000	790	65 000	450	40	40	40
301	S30100	100 000	690	55 000	380	40	40	40
302	S30200	100 000	690	55 000	380	35	35	35
304	S30400	100 000	690	55 000	380	35	35	35
304L	S30403	100 000	690	55 000	380	30	30	30
304N	S30451	100 000	690	55 000	380	37	37	37
304LN	—	100 000	690	55 000	380	33	33	33
316	S31600	100 000	690	55 000	380	30	30	30
316L	S31603	100 000	690	55 000	380	25	25	25
316N	S31651	100 000	690	55 000	380	32	32	32

¼ Hard

Type	UNS designation	Tensile strength, min psi	Tensile strength, min MPa	Yield strength, min psi	Yield strength, min MPa	Elongation in 2 in or 50 mm, min, % <0.015 in	Elongation in 2 in or 50 mm, min, % ≥0.015 to ≤0.030 in	Elongation in 2 in or 50 mm, min, % >0.030 in
201	S20100	125 000	860	75 000	515	25	25	25
202	S20200	125 000	860	75 000	515	12	12	—
205	S20500	125 000	860	75 000	515	45	45	45
301	S30100	125 000	860	75 000	515	25	25	25
302	S30200	125 000	860	75 000	515	10	10	12
304	S30400	125 000	860	75 000	515	10	10	12
304L	S30403	125 000	860	75 000	515	8	8	10
304N	S30451	125 000	860	75 000	515	12	12	12
304LN	—	125 000	860	75 000	515	10	10	12
316	S31600	125 000	860	75 000	515	10	10	10
316L	S31603	125 000	860	75 000	515	8	8	8
316N	S31651	125 000	860	75 000	515	12	12	12
XM-11	S21904	130 000	895	115 000	795	15	15	—

½ Hard

Type	UNS designation	Tensile strength, min psi	Tensile strength, min MPa	Yield strength, min psi	Yield strength, min MPa	Elongation in 2 in or 50 mm, min, % <0.015 in	Elongation in 2 in or 50 mm, min, % ≥0.015 to ≤0.030 in	Elongation in 2 in or 50 mm, min, % >0.030 in
201	S20100	150 000	1035	110 000	760	15	18	18
205	S20500	150 000	1035	110 000	760	15	18	18
301	S30100	150 000	1035	110 000	760	15	18	18

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TABLE 4.4 Tensile Property Requirements[a] (*Continued*)

½ Hard

Type	UNS designation	Tensile strength, min psi	Tensile strength, min MPa	Yield strength, min psi	Yield strength, min MPa	Elongation in 2 in or 50 mm, min, % <0.015 in	Elongation in 2 in or 50 mm, min, % ≥0.015 to ≤0.030 in	Elongation in 2 in or 50 mm, min, % >0.030 in
302	S30200	150 000	1035	110 000	760	9	10	10
304	S30400	150 000	1035	110 000	760	6	7	7
304L	S30403	150 000	1035	110 000	760	5	6	6
304N	S30451	150 000	1035	110 000	760	6	8	8
304LN	—	150 000	1035	110 000	760	6	7	7
316	S31600	150 000	1035	110 000	760	6	7	7
316L	S31603	150 000	1035	110 000	760	5	6	6
316N	S31651	150 000	1035	110 000	760	6	8	8

¾ Hard

Type	UNS designation	Tensile strength, min psi	Tensile strength, min MPa	Yield strength, min psi	Yield strength, min MPa	Elongation in 2 in or 50 mm, min, % <0.015 in	Elongation in 2 in or 50 mm, min, % ≥0.015 to ≤0.030 in	Elongation in 2 in or 50 mm, min, % >0.030 in
201	S20100	175 000	1205	135 000	930	10	12	12
205	S20500	175 000	1205	135 000	930	15	15	15
301	S30100	175 000	1205	135 000	930	10	12	12
302	S30200	175 000	1205	135 000	930	5	6	6

Full Hard

Type	UNS designation	Tensile strength, min psi	Tensile strength, min MPa	Yield strength, min psi	Yield strength, min MPa	Elongation in 2 in or 50 mm, min, % <0.015 in	Elongation in 2 in or 50 mm, min, % ≥0.015 to ≤0.030 in	Elongation in 2 in or 50 mm, min, % >0.030 in
201	S20100	185 000	1275	140 000	965	8	9	9
205	S20500	185 000	1275	140 000	965	10	10	10
301	S30100	185 000	1275	140 000	965	8	9	9
302	S30200	185 000	1275	140 000	965	3	4	4

[a] This specification defines minimum properties only and does not imply a range. Depending on the work hardening characteristics of the particular grade, either the yield or the tensile strength can be the controlling factor in meeting the properties. The noncontrolling factor normally will exceed considerably the specified minimum.

[b] Type 201 is generally produced with a chemical composition balanced for rich side (type 201-1) or lean side (type 201-2), austenite stability depending on the properties required for specific applications.

[c] Annealed material that naturally meets mechanical properties may be applied.

[d] PSS means plate, strip, sheet.

[e] FB means flat bar.

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TABLE 4.5 Estimated Mechanical Properties and Machinability Ratings of Nonresulfurized Carbon Steel Bars, Manganese 1.00% Maximum

			Estimated minimum values							
			Tensile strength		Yield strength					
UNS no.	SAE and/or AISI no.	Type of processing	psi	MPa	psi	MPa	Elongation in 2 in, %	Reduction in area, %	Brinell hardness	Average machinability rating (cold drawn 1212 = 100%)
G10060	1006	Hot rolled	43 000	300	24 000	170	30	55	86	
		Cold drawn	48 000	330	41 000	280	20	45	95	50
G10080	1008	Hot rolled	44 000	303	24 500	170	30	55	86	
		Cold drawn	49 000	340	41 500	290	20	45	95	55
G10100	1010	Hot rolled	47 000	320	26 000	180	28	50	95	
		Cold drawn	53 000	370	44 000	300	20	40	105	55
G10120	1012	Hot rolled	48 000	330	26 500	180	28	50	95	
		Cold drawn	54 000	370	45 000	310	19	40	105	55
G10150	1015	Hot rolled	50 000	340	27 500	190	28	50	101	
		Cold drawn	56 000	390	47 000	320	18	40	111	60
G10160	1016	Hot rolled	55 000	380	30 000	210	25	50	111	
		Cold drawn	61 000	420	51 000	350	18	40	121	70
G10170	1017	Hot rolled	53 000	370	29 000	200	26	50	105	
		Cold drawn	59 000	410	49 000	340	18	40	116	65
G10180	1018	Hot rolled	58 000	400	32 000	220	25	50	116	
		Cold drawn	64 000	440	54 000	370	15	40	126	70
G10190	1019	Hot rolled	59 000	410	32 500	220	25	50	116	
		Cold drawn	66 000	460	55 000	380	15	40	131	70
G10200	1020	Hot rolled	55 000	380	30 000	210	25	50	111	
		Cold drawn	61 000	420	51 000	350	15	40	121	65
G10210	1021	Hot rolled	61 000	420	33 000	230	24	48	116	
		Cold drawn	68 000	470	57 000	390	15	40	131	70
G10220	1022	Hot rolled	62 000	430	34 000	230	23	47	151	
		Cold drawn	69 000	480	58 000	400	15	40	137	70
G10230	1023	Hot rolled	56 000	370	31 000	210	25	50	111	
		Cold drawn	62 000	430	52 500	360	15	40	121	65

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G10250	1025	Hot rolled	58 000	400	32 000	220	25	50	116	
		Cold drawn	64 000	440	54 000	370	15	40	126	65
G10260	1026	Hot rolled	64 000	440	35 000	240	24	49	126	
		Cold drawn	71 000	490	60 000	410	15	40	143	75
G10300	1030	Hot rolled	68 000	470	37 500	260	20	42	137	
		Cold drawn	76 000	520	64 000	440	12	35	149	70
G10350	1035	Hot rolled	72 000	500	39 500	270	18	40	143	
		Cold drawn	80 000	550	67 000	460	12	35	163	65
G10370	1037	Hot rolled	74 000	510	40 500	280	18	40	143	
		Cold drawn	82 000	570	69 000	480	12	35	167	65
G10380	1038	Hot rolled	75 000	520	41 000	280	18	40	149	
		Cold drawn	83 000	570	70 000	480	12	35	163	65
G10390	1039	Hot rolled	79 000	540	43 500	300	16	40	156	
		Cold drawn	88 000	610	74 000	510	12	35	179	60
G10400	1040	Hot rolled	76 000	520	42 000	290	18	40	149	
		Cold drawn	85 000	590	71 000	490	12	35	170	60
G10420	1042	Hot rolled	80 000	550	44 000	300	16	40	163	
		Cold drawn	89 000	610	75 000	520	12	35	179	60
		NCD†	85 000	590	73 000	500	12	45	179	70
G10430	1043	Hot rolled	82 000	570	45 000	310	16	40	163	
		Cold drawn	91 000	630	77 000	530	12	35	179	60
		NCD†	87 000	600	75 000	520	12	45	179	70
G10440	1044	Hot rolled	80 000	550	44 000	300	16	40	163	
G10450	1045	Hot rolled	82 000	570	45 000	310	16	40	163	
		Cold drawn	91 000	630	77 000	530	12	35	179	55
		ACD*	85 000	590	73 000	500	12	45	170	65
G10460	1046	Hot rolled	85 000	590	47 000	320	15	40	170	
		Cold drawn	94 000	650	79 000	540	12	35	187	55
		ACD*	90 000	620	75 000	520	12	45	179	65
G10490	1049	Hot rolled	87 000	600	48 000	330	15	35	179	
		Cold drawn	97 000	670	81 500	560	10	30	197	45
		ACD*	92 000	630	77 000	530	10	40	187	55

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TABLE 4.5 Estimated Mechanical Properties and Machinability Ratings of Nonresulfurized Carbon Steel Bars, Manganese 1.00% Maximum (*Continued*)

UNS no.	SAE and/or AISI no.	Type of processing	Estimated minimum values: Tensile strength psi	Tensile strength MPa	Yield strength psi	Yield strength MPa	Elongation in 2 in, %	Reduction in area, %	Brinell hardness	Average machinability rating (cold drawn 1212 = 100%)
G10500	1050	Hot rolled	90 000	620	49 500	340	15	35	179	
		Cold drawn	100 000	690	84 000	580	10	30	197	45
		ACD*	95 000	660	80 000	550	10	40	189	55
G10550	1055	Hot rolled	94 000	650	51 500	360	12	30	192	
		ACD*	96 000	660	81 000	560	10	40	197	55
G10600	1060	Hot rolled	98 000	680	54 000	370	12	30	201	
		SACD‡	90 000	620	70 000	480	10	45	183	60
G10640	1064	Hot rolled	97 000	670	53 500	370	12	30	201	
		SACD‡	89 000	610	69 000	480	10	45	183	60
G10650	1065	Hot rolled	100 000	690	55 000	380	12	30	207	
		SACD‡	92 000	630	71 000	490	10	45	187	60
G10700	1070	Hot rolled	102 000	700	56 000	390	12	30	212	
		SACD‡	93 000	640	72 000	500	10	45	192	55
G10740	1074	Hot rolled	105 000	720	58 000	400	12	30	217	
		SACD‡	94 500	650	73 000	500	10	40	192	55
G10780	1078	Hot rolled	100 000	690	55 000	380	12	30	207	
		SACD‡	94 000	650	72 500	500	10	40	192	55
G10800	1080	Hot rolled	112 000	770	61 500	420	10	25	229	
		SACD‡	98 000	680	75 000	520	10	40	192	45
G10840	1084	Hot rolled	119 000	820	65 500	450	10	25	241	
		SACD‡	100 000	690	77 000	530	10	40	192	45
G10850	1085	Hot rolled	121 000	830	66 500	460	10	25	248	
		SACD‡	100 500	690	78 000	540	10	40	192	45
G10860	1086	Hot rolled	112 000	770	61 500	420	10	25	229	
		SACD‡	97 000	670	74 000	510	10	40	192	45

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G10900	1090	Hot rolled	122 000	840	67 000	460	10	25	248		
		SACD‡	101 000	700	78 000	540	10	40	197	45	
G10950	1095	Hot rolled	120 000	830	66 000	460	10	25	248		
		SACD‡	99 000	680	76 000	520	10	40	197	45	

* ACD represents annealed cold drawn.
† NCD represents normalized cold drawn.
‡ SACD represents spheroidized annealed cold drawn.
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TABLE 4.6 Estimated Mechanical Properties and Machinability Ratings of Resulfurized Carbon Steel Bars*

UNS no.	SAE and/or AISI no.	Type of processing	Estimated minimum values: Tensile strength psi	Tensile strength MPa	Yield strength psi	Yield strength MPa	Elongation in 2 in, %	Reduction in area, %	Brinell hardness	Average machinability rating (cold drawn 1212 = 100%)
G11080	1108	Hot rolled	50 000	340	27 500	190	30	50	101	
		Cold drawn	56 000	390	47 000	320	20	40	121	80
G11170	1117	Hot rolled	62 000	430	34 000	230	23	47	121	
		Cold drawn	69 000	480	58 000	400	15	40	137	90
G11320	1132	Hot rolled	83 000	570	45 500	310	16	40	167	
		Cold drawn	92 000	630	77 000	530	12	35	183	75
G11370	1137	Hot rolled	88 000	610	48 000	330	15	35	179	
		Cold drawn	98 000	680	82 000	570	10	30	197	70
G11400	1140	Hot rolled	79 000	540	43 500	300	16	40	156	
		Cold drawn	88 000	610	74 000	510	12	35	170	70
G11410	1141	Hot rolled	94 000	650	51 500	360	15	35	187	
		Cold drawn	105 100	720	88 000	610	10	30	212	70
G11440	1144	Hot rolled	97 000	670	53 000	370	15	35	197	
		Cold drawn	108 000	740	90 000	620	10	30	217	80
G11460	1146	Hot rolled	85 000	590	47 000	320	15	40	170	
		Cold drawn	94 000	650	80 000	550	12	35	187	70
G11510	1151	Hot rolled	92 000	630	50 500	340	15	35	187	
		Cold drawn	102 000	700	86 000	590	10	30	207	65
G12110	1211	Hot rolled	55 000	380	33 000	230	25	45	121	
		Cold drawn	75 000	520	58 000	400	10	35	163	95
G12120	1212	Hot rolled	56 000	390	33 500	230	25	45	121	
		Cold drawn	78 000	540	60 000	410	10	35	167	100
G12130	1213	Hot rolled	56 000	390	33 500	230	25	45	121	
		Cold drawn	78 000	540	60 000	410	10	35	167	135
G12144	12L14	Hot rolled	57 000	390	34 000	230	22	45	121	
		Cold drawn	78 000	540	60 000	410	10	35	163	160

* All 1100 and 1200 series steels are rated on the basis of 0.10% max. silicon or coarse grain melting practice.

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TABLE 4.7 Estimated Mechanical Properties and Machinability Ratings of Nonresulfurized Carbon Steel Bars, Manganese Maximum over 1.00%

UNS no.	SAE and/or AISI no.	Type of processing	Estimated minimum values: Tensile strength psi	Tensile strength MPa	Yield strength psi	Yield strength MPa	Elongation in 2 in, %	Reduction in area, %	Brinell hardness	Average machinability rating (cold drawn 1212 = 100%)
G15240	1524	Hot rolled	74 000	510	41 000	280	20	42	149	
		Cold drawn	82 000	570	69 000	480	12	35	163	60
G15270	1527	Hot rolled	75 000	520	41 000	280	18	40	149	
		Cold drawn	83 000	570	70 000	480	12	35	163	65
G15360	1536	Hot rolled	83 000	570	45 500	310	16	40	163	
		Cold drawn	92 000	630	77 500	530	12	35	187	55
G15410	1541	Hot rolled	92 000	630	51 000	350	15	40	187	
		Cold drawn	102 500	710	87 000	600	10	30	207	45
		ACD*	94 000	650	80 000	550	10	45	184	60
G15480	1548	Hot rolled	96 000	660	53 000	370	14	33	197	
		Cold drawn	106 500	730	89 500	620	10	28	217	45
		ACD*	93 500	640	78 500	540	10	35	192	50
G15520	1552	Hot rolled	108 000	740	59 500	410	12	30	217	
		ACD*	98 000	680	83 000	570	10	40	193	50

* ACD represents annealed cold drawn.

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TABLE 4.8 Machinability of Alloy Steels

UNS no.	AISI and/or SAE no.	Machinability rating	Condition	Range of typical hardness HB	Microstructure type
G13300	1330	55	Annealed and cold drawn	179/235	A
G13350	1335	55	Annealed and cold drawn	179/235	A
G13400	1340	50	Annealed and cold drawn	183/241	A
G13450	1345	45	Annealed and cold drawn	183/241	A
G40230	4023	70	Cold drawn	156/207	C
G40240	4024	75	Cold drawn	156/207	C
G40270	4027	70	Annealed and cold drawn	167/212	A
G40280	4028	75	Annealed and cold drawn	167/212	A
G40320	4032	70	Annealed and cold drawn	174/217	A
G40370	4037	70	Annealed and cold drawn	174/217	A
G40420	4042	65	Annealed and cold drawn	179/229	A
G40470	4047	65	Annealed and cold drawn	179/229	A
G41180	4118	60	Cold drawn	170/207	C
G41300	4130	70	Annealed and cold drawn	187/229	A
G41350	4135	70	Annealed and cold drawn	187/229	A
G41370	4137	70	Annealed and cold drawn	187/229	A
G41400	4140	65	Annealed and cold drawn	187/229	A
G41420	4142	65	Annealed and cold drawn	187/229	A
G41450	4145	60	Annealed and cold drawn	187/229	A
G41470	4147	60	Annealed and cold drawn	187/235	A
G41500	4150	55	Annealed and cold drawn	187/241	A, B
G41610	4161	50	Spheroidized and cold drawn	187/241	B, A
G43200	4320	60	Annealed and cold drawn	187/229	D, B, A
G43400	4340	50	Annealed and cold drawn	187/241	B, A
G43406	E4340	50	Annealed and cold drawn	187/241	B, A
G44220	4422	65	Cold drawn	170/212	C
G44270	4427	65	Annealed and cold drawn	170/212	A

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G46150	4615	65	Cold drawn	174/223	C
G46170	4617	65	Cold drawn	174/223	C
G46200	4620	65	Cold drawn	183/229	C
G46260	4626	70	Cold drawn	170/212	C
G47180	4718	60	Cold drawn	187/229	C
G47200	4720	65	Cold drawn	187/229	C
G48150	4815	50	Annealed and cold drawn	187/229	D, B
G48170	4817	50	Annealed and cold drawn	187/229	D, B
G48200	4820	50	Annealed and cold drawn	187/229	D, B
G50401	50B40	65	Annealed and cold drawn	174/223	A
G50441	50B44	65	Annealed and cold drawn	174/223	A
G50460	5046	60	Annealed and cold drawn	174/223	A
G50461	50B46	60	Annealed and cold drawn	174/223	A
G50501	50B50	55	Annealed and cold drawn	183/235	A
G50600	5060	55	Spheroidized annealed and cold drawn	170/212	B
G50601	50B60	55	Spheroidized annealed and cold drawn	170/212	B
G51150	5115	65	Cold drawn	163/201	C
G51200	5120	70	Cold drawn	163/201	C
G51300	5130	70	Annealed and cold drawn	174/212	A
G51320	5132	70	Annealed and cold drawn	174/212	A
G51350	5135	70	Annealed and cold drawn	179/217	A
G51400	5140	65	Annealed and cold drawn	179/217	A
G51470	5147	65	Annealed and cold drawn	179/229	A
G51500	5150	60	Annealed and cold drawn	183/235	A, B
G51550	5155	55	Annealed and cold drawn	183/235	A, B
G51600	5160	55	Spheroidized annealed and cold drawn	179/217	B
G51601	51B60	55	Spheroidized annealed and cold drawn	179/217	B
G50986	50100	40	Spheroidized annealed and cold drawn	183/241	B
G51986	51100	40	Spheroidized annealed and cold drawn	183/241	B
G52986	52100	40	Spheroidized annealed and cold drawn	183/241	B
G61180	6118	60	Cold drawn	179/217	C
G61500	6150	55	Annealed and cold drawn	183/241	B, A
G81150	8115	65	Cold drawn	163/202	C

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TABLE 4.8 Machinability of Alloy Steels (*Continued*)

UNS no.	AISI and/or SAE no.	Machinability rating	Condition	Range of typical hardness HB	Microstructure type
G81451	81B45	65	Annealed and cold drawn	179/223	A
G86150	8615	70	Cold drawn	179/235	C
G86170	8617	70	Cold drawn	179/235	C
G86200	8620	65	Cold drawn	179/235	C
G86220	8622	65	Cold drawn	179/235	C
G86250	8625	60	Annealed and cold drawn	179/223	A
G86270	8627	60	Annealed and cold drawn	179/223	A
G86300	8630	70	Annealed and cold drawn	179/229	A
G86370	8637	65	Annealed and cold drawn	179/229	A
G86400	8640	65	Annealed and cold drawn	184/229	A
G86420	8642	65	Annealed and cold drawn	184/229	A
G86450	8645	65	Annealed and cold drawn	184/235	A
G86451	86B45	65	Annealed and cold drawn	184/235	A
G86500	8650	60	Annealed and cold drawn	187/248	A, B
G86550	8655	55	Annealed and cold drawn	187/248	A, B
G86600	8660	55	Spheroidized annealed and cold drawn	179/217	B
G87200	8720	65	Cold drawn	179/235	C
G87400	8740	65	Annealed and cold drawn	184/235	A
G88220	8822	55	Cold drawn	179/223	B
G92540	9254	45	Spheroidized annealed and cold drawn	187/241	B
G92600	9260	40	Spheroidized annealed and cold drawn	184/235	B
G93106	9310	50	Annealed and cold drawn	184/229	D
G94151	94B15	70	Cold drawn	163/202	C
G94171	94B17	70	Cold drawn	163/202	C
G94301	94B30	70	Annealed and cold drawn	170/223	A

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TABLE 4.9 Typical Treatments for Case Hardening Grades of Carbon Steels

UNS no.	SAE steels*	Carburizing temperature, °F	°C	Cooling medium	Reheat temperature, °F	°C	Cooling medium	Carbonitriding temperature, °F†	°C†	Cooling medium	Temper °F	°C‡
G10100	1010	—	—	—	—	—	—	1450–1650	790–900	Oil	250–400	120–205
G10150	1015	—	—	—	—	—	—	1450–1650	790–900	Oil	250–400	120–205
G10160	1016	1650–1700	900–925	Water or caustic	—	—	—	1450–1650	790–900	Oil	250–400	120–205
G10180	1018	1650–1700	900–925	Water or caustic	1450	790	Water or caustic§	1450–1650	790–900	Oil	250–400	120–205
G10200	1020	1650–1700	900–925	Water or caustic	1450	790	Water or caustic§	1450–1650	790–900	Oil	250–400	120–205
G10220	1022	1650–1700	900–925	Water or caustic	1450	790	Water or caustic§	1450–1650	790–900	Oil	250–400	120–205
G10260	1026	1650–1700	900–925	Water or caustic	1450	790	Water or caustic§	1450–1650	790–900	Oil	250–400	120–205
G10300	1030	1650–1700	900–925	Water or caustic	1450	790	Water or caustic§	1450–1650	790–900	Oil	250–400	120–205
G11170	1117	1650–1700	900–925	Water or oil	1450–1600	790–870	Water or caustic§	1450–1650	790–900	Oil	250–400	120–205
G11180	1118	1650–1700	900–925	Oil	1450–1600	790–870	Oil	—	—	—	250–400	120–205
G15130	1513	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205
G15220	1522	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205
G15240	1524	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205
G15260	1526	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205
G15270	1527	1650–1700	900–925	Oil	1450	790	Oil	—	—	—	250–400	120–205

* Generally, it is not necessary to normalize the carbon grades for fulfilling either dimensional or machinability requirements of parts made from the steel grades listed in the table although, where dimension is of vital importance, normalizing temperatures of at least 50°F above the carburizing temperatures are sometimes required.

† The higher manganese steels such as 1118 and the 1500 series are not usually carbonitrided. If carbonitriding is performed, care must be taken to limit the nitrogen content because high nitrogen will increase their tendency to retain austenite.

‡ Even where recommended tempering temperatures are shown, the temper is not mandatory on many applications. Tempering is generally employed for a partial stress relief and improves resistance to cracking from grinding operations. Higher temperatures than those shown may be employed where the hardness specification on the finished parts permits.

§ 3% sodium hydroxide.

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TABLE 4.10 Typical Treatments for Heat Treating Grades of Carbon Steels

UNS no.	SAE steels	Normalizing temperature, °F	°C	Annealing temperature, °F	°C	Hardening temperature, °F	°C	Quenching medium*
G10300	1030	—	—	—	—	1575–1600	855–870	Water or caustic
G10350	1035	—	—	—	—	1550–1600	840–870	Water or caustic
G10380†	1038†	—	—	—	—	1525–1575	830–855	Water or caustic
G10390†	1039†	—	—	—	—	1525–1575	830–855	Water or caustic
G10400†	1040†	—	—	—	—	1525–1575	830–855	Water or caustic
G10420	1042	—	—	—	—	1500–1550	815–845	Water or caustic
G10430†	1043†	—	—	—	—	1500–1550	815–845	Water or caustic
G10450†	1045†	—	—	—	—	1500–1550	815–845	Water or caustic
G10460†	1046†	—	—	—	—	1500–1550	815–845	Water or caustic
G10500†	1050†	1600–1700	870–925	—	—	1500–1550	815–845	Water or caustic
G10530	1053	1600–1700	870–925	—	—	1500–1550	815–845	Water or caustic
G10600	1060	1600–1700	870–925	1400–1500	760–815	1575–1625	855–885	Oil
G10740	1074	1550–1650	870–900	1400–1500	760–815	1575–1625	855–885	Oil
G10800	1080	1550–1650	845–900	1400–1500‡	760–815‡	1575–1625	855–885	Oil§
G10900	1090	1550–1650	845–900	1400–1500‡	760–815‡	1575–1625	855–885	Oil§
G10950	1095	1550–1650	845–900	1400–1500‡	760–815‡	1575–1625	855–885	Water and oil
G11370	1137	—	—	—	—	1550–1600	845–870	Oil
G11410	1141	—	—	1400–1500	760–815	1500–1550	815–845	Oil
G11440	1144	1600–1700	870–925	1400–1500	760–815	1500–1550	815–845	Oil
G11450	1145	—	—	—	—	1475–1500	800–815	Water or oil
G11460	1146	—	—	—	—	1475–1500	800–815	Water or oil
G15410	1541	1600–1700	870–925	1400–1500	760–815	1500–1550	815–845	Water or oil
G15480	1548	1600–1700	870–925	—	—	1500–1550	815–845	Oil
G15520	1552	1600–1700	870–925	—	—	1500–1550	815–845	Oil
G15660	1566	1600–1700	870–925	—	—	1575–1625	855–885	Oil

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* All steels are tempered to desired hardness; however, tempering is not mandatory on many applications. Tempering is generally employed for a partial stress relief and improves resistance to cracking from grinding operations. Higher temperatures than those shown may be employed where the hardness specification on the finished parts permits.

† Commonly used on parts where induction hardening is employed. However, all steels from SAE 1030 up may have induction hardening applications.

‡ Spheroidal structures are often required for machining purposes and should be cooled very slowly or be isothermally transformed to produce the desired structure.

§ May be water or brine quenched by special techniques such as partial immersion or time quenched; otherwise they are subject to quench cracking.

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TABLE 4.11 Typical Heat Treatments for Carburizing Grades of Alloy Steels

UNS no.	SAE steels[a]	Pretreatments			Carburizing[e] temperature, °F	°C	Cooling method	Reheat[i] temperature, °F	°C	Quenching medium	Tempering[f] temperature, °F	°C
		Normalize[b]	Normalize and temper[c]	Cycle anneal[d]								
G40120	4012											
G40230	4023											
G40270	4027	Yes	—	—	1650–1700	900–925	Quench in oil[g]	—	—	—	250–350	120–175
G40280	4028											
G40320	4032											
G41180	4118	Yes	—	—	1650–1700	900–925	Quench in oil[g]	—	—	—	250–350	120–175
G43200	4320	Yes	—	Yes	1650–1700	900–925	Quench in oil[g]	—	—	—	250–350	120–175
					1650–1700	900–925	Cool slowly	1525–1550[h]	830–845	Oil	250–350	120–175
G44220	4422	Yes	—	Yes	1650–1700	900–925	Quench in oil[g]	—	—	—	250–350	120–175
G44270	4427											
G46200	4620	Yes	—	Yes	1650–1700	900–925	Cool slowly	1500–1550[h]	815–845	Oil	250–350	120–175
G47200	4720	Yes	—	Yes	1650–1700	900–925	Quench in oil	1500–1550[h]	815–845	Oil	250–350	120–175
G48150	4815	—	Yes	Yes	1650–1700	900–925	Quench in oil[g]	—	—	—	250–325	120–175
G48200	4820				1650–1700	900–925	Quench in oil	1475–1525[h]	800–830	Oil	250–325	120–175
G51200	5120	Yes	—	—	1650–1700	900–925	Quench in oil[g]	—	—	—	250–350	120–175
G86150	8615	Yes	—	—								
G86170	8617											
G86200	8620				1650–1700	900–925	Quench in oil[g]	—	845–870	—	250–350	120–175
G86220	8622				1650–1700	900–925	Cool slowly	1550–1600[h]	845–870	Oil	250–350	120–175
G86250	8625				1650–1700	900–925	Quench in oil	1550–1600[h]	845–870	Oil	250–350	120–175
G86270	8627	Yes	—	Yes								
G87200	8720											
G88220	8822											
G93100	9310	—	Yes	—	1600–1700	900–925	Quench in oil	1450–1525[h]	790–830	Oil	250–325	120–175
					1600–1700	900–925	Cool slowly	1450–1525[h]	790–830	Oil	250–325	120–175
G94151	94B15	Yes	—	—	1650–1700	900–925	Quench in oils	—	—	—	250–350	120–175
G94171	94B17											

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[a] These steels are fine grain. Heat treatments are not necessarily correct for coarse grain.

[b] Normalizing temperature should be at least as high as the carburizing temperature followed by air cooling.

[c] After normalizing, reheat to temperature of 1100–1200°F and hold at temperature approximately 1 h per in of maximum section or 4 h minimum time.

[d] Where cycle annealing is desired, heat to at least as high as the carburizing temperature, hold for uniformity, cool rapidly to 1000–1250°F, hold 1 to 3 h, then air cool or furnace cool to obtain a structure suitable for machining and finish.

[e] It is general practice to reduce carburizing temperatures to approximately 1550°F before quenching to minimize distortion and retained austenite. For 4800 series steels, the carburizing temperature is reduced to approximately 1500°F before quenching.

[f] Tempering treatment is optional. Tempering is generally employed for partial stress relief and improved resistance to cracking from grinding operations. Temperatures higher than those shown are used in some instances where application requires.

[g] This treatment is most commonly used and generally produces a minimum of distortion.

[h] This treatment is used where the maximum grain refinement is required and/or where parts are subsequently ground on critical dimensions. A combination of good case and core properties is secured with somewhat greater distortion than is obtained by a single quench from the carburizing treatment.

[i] In this treatment the parts are slowly cooled, preferably under a protective atmosphere. They are then reheated and oil quenched. A tempering operation follows as required. This treatment is used when machining must be done between carburizing and hardening or when facilities for quenching from the carburizing cycle are not available. Distortion is at least equal to that obtained by a single quench from the carburizing cycle, as described in note e.

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TABLE 4.12 Typical Heat Treatments for Directly Hardenable Grades of Alloy Steels

UNS no.	SAE steels[a]	Normalizing temperature, °F	°C	Annealing[d] temperature, °F	°C	Hardening[e] temperature, °F	°C	Quenching medium[f]
G13300	1330	1600–1700[b]	870–925[b]	1550–1650	845–900	1525–1575	830–855	Water or oil
G13350	1335	1600–1700[b]	870–925[b]	1550–1650	845–900	1500–1550	815–845	Oil
G13400	1340							
G40370	4037	—		1500–1575	815–855	1525–1575	830–855	Oil
G40470	4047	—		1450–1550	790–845	1500–1575	815–855	Oil
G41300	4130	1600–1700[b]	870–925[b]	1450–1550	790–845	1500–1600	815–870	Water or oil
G41370	4137							
G41400	4140	—		1450–1550	790–845	1550–1600	845–900	Oil
G41420	4142							
G41450	4145							
G41470	4147	—		1450–1550	790–845	1500–1550	815–845	Oil
G41450	4140							
G43400	4340	1600–1700[b,c]	870–925[b,c]	1450–1550	790–845	1500–1550	815–845	Oil
G50461	5046	1600–1700[b]	870–925[b]	1500–1600	815–870	1500–1550	815–845	Oil
G51300	5130	1600–1700[b]	870–925[b]	1450–1550	790–845	1525–1575	830–855	Water, caustic solution, or oil
G51320	5132							
G51400	5140	1600–1700[b]	870–925[b]	1500–1600	815–870	1500–1550	815–845	Oil
G51500	5150							
G51600	5160	1600–1700[b]	870–925[b]	1500–1600	815–870	1475–1550	800–845	Oil
G51601	5160							
G61500	6150	—		1550–1650	845–900	1550–1625	845–885	Oil

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G86300	8630	1600–1700[b]	870–925[b]	1450–1550	790–845	1525–1600	830–870	Water or oil
G86370	8637	—		1500–1600	815–870	1525–1575	830–855	Oil
G86400	8640							
G86450	8645	—		1500–1600	815–870	1500–1575	815–855	Oil
G92600	9260	—		—	—	1500–1650	815–900	Oil

[a] These steels are fine grain unless otherwise specified.
[b] These steels should be either normalized or annealed for optimum machinability.
[c] Temper at 1100–1225°F (595–665°C).
[d] The specific annealing cycle is dependent on the alloy content of the steel, the type of subsequent machining operations, and the desired surface finish.
[e] Frequently, these steels, with the exception of 4340, 50100, 51100, and 52100, are hardened and tempered to a final machinable hardness without preliminary heat treatment.
[f] All steels are tempered to desired hardness.
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TABLE 4.13 Typical Heat Treatments for Grades of Chromium-Nickel Austenitic Steels Not Hardenable by Thermal Treatment

SAE steels	AISI no.	Annealing temperature, °F*	°C
20201	201	1850–2050	1010–1120
20202	202	1850–2050	1010–1120
30301	301	1850–2050	1010–1120
30302	302	1850–2050	1010–1120
30303	303	1850–2050	1010–1120
30304	304	1850–2050	1010–1120
30305	305	1850–2050	1010–1120
30309	309	1900–2050	1040–1120
30310	310	1900–2100	1040–1150
30316	316	1850–2050	1010–1120
30317	317	1850–2050	1010–1120
30321	321	1750–2050	955–1120
30325	325	1800–2100	980–1150
30330	—	1950–2150	1065–1175
30347	347	1850–2050	1010–1120

* Quench to produce full austenitic structure using water or air in accordance with thickness of section. Annealing temperatures given cover process and full annealing as already established and used by industry, the lower end of the range being used for process annealing. All steels are quenched in air.

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TABLE 4.14 Typical Heat Treatments for Stainless Chromium Steels

SAE steels	AISI no.	Subcritical annealing temperature, °F	°C	Full annealing temperature, °F*	°C	Hardening temperature, °F	°C	Quenching medium¶
51409	—	—		1625	885	—	—	Air
51410	410	1300–1350†	705–730†	1500–1650	815–900	1700–1850	925–1010	Oil or air
51414	414	1200–1250†	650–675†	—	—	1800–1900	980–1040	Oil or air
51416	416	1300–1350§	705–730†	1500–1650	815–900	1700–1850	925–1010	Oil or air
51420	420	1350–1450†	730–790†	1550–1650	845–900	1800–1900	980–1040	Oil or air
51420F*	—	1350–1450†	730–790†	1550–1650	845–900	1800–1900	980–1040	Oil or air
51430	430	1400–1500§	760–815§	—	—	—	—	—
51430F‡	—	1250–1400§	675–760§	—	—	—	—	—
51431	431	1150–1225†	620–665†	—	—	1800–1950	980–1065	Oil or air
51434	—	1400–1600§	760–870§	—	—	—	—	—
51436	—	1400–1600§	760–870§	—	—	—	—	—
51440A‡	440A	1350–1440†	730–780†	1550–1650	845–900	1850–1950	1010–1065	Oil or air
51440B‡	440B	1350–1440†	730–780†	1550–1650	845–900	1850–1950	1010–1065	Oil or air
51440C‡	440C	1350–1440†	730–780†	1550–1650	845–900	1850–1950	1010–1065	Oil or air
51440F‡	—	1350–1440†	730–780†	1550–1650	845–900	1850–1950	1010–1065	Oil or air
51442	442	1350–1500§	730–815§	—	—	—	—	—
51446	446	1450–1600§	790–870†	—	—	—	—	—
51501	501	1325–1375§	720–745§	1525–1600	830–870	1600–1700	870–925	Oil or air

* Cool slowly in furnace.
† Usually air cooled but may be furnace cooled.
‡ Suffixes A, B, and C denote three types of steel differing only in carbon content. Suffix F denotes a free machining steel.
§ Cool rapidly in air.
¶ All steels are tempered to desired hardness.
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TABLE 4.15 Typical Heat Treatments for Wrought Stainless Steels of Special Machinability

Proprietary designation	Subcritical annealing temperature, °F	°C	Full annealing temperature, °F	°C	Quenching medium
203-EZ	—	—	1850–2050*	1010–1120*	Water or air
303 Ma	—	—	1850–2050*	1010–1120*	Water or air
303 Cu	—	—	1850–2050*	1010–1120*	Water or air
303 Plus X	—	—	1850–2050*	1010–1120*	Water or air
416 Plus X	1300–1350†	705–730†	1550–1650‡	845–900*	—

* Quench to produce full austenitic structure using water or air in accordance with thickness of section. Annealing temperatures given cover process and full annealing as already established and used by industry, the lower end of the range being used for process annealing.

† Usually air cooled but may be furnace cooled.

‡ Cool slowly in the furnace.

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TABLE 4.16 Monotonic Stress-Strain Properties of Selected Metals (Sort: Steel, A1, SAE Spec., Increasing True Fracture Strength)

SAE spec	BHn	Grain dir	Process description	Ultimate strength, ksi (MPa)	Yield strength, ksi (MPa)	True fracture strength, ksi (MPa)	%RA	True fracture ductility	Strain hard'G exponent	Strength coefficient, ksi (MPa)
A-538-A†	405	L	Sol tr & aged	220 (1517)	215 (1482)	275 (1896)	67	1.10	0.030	
A-538-B†	460	L	Sol tr & aged	270 (1862)	260 (1793)	310 (2137)	56	0.82	0.020	
A-538-C†	480	L	Sol tr & aged	290 (1999)	280 (1931)	325 (2241)	55	0.81	0.015	
AM-350†		L	HR & annealed	191 (1317)	64 (441)	298 (2055)	52	0.74		
AM-350¶	496	L	CD	276 (1903)	270 (1862)	316 (2179)	20	0.23		
Gainex¶		LT	HR sheet	77 (531)	58 (400)	117 (807)	58	0.86	0.20	
Gainex‡		L	HR sheet	74 (510)	57 (393)	118 (814)	64	1.02	0.20	
H-11	660	L	Ausformed	375 (2586)	295 (2034)	460 (3172)	33	0.40	0.120	
R-100§	236	LT	As rec plate	177 (1220)	117 (807)	214 (1475)				
R-100§	236	L	As rec plate	169 (1165)	112 (772)	236 (1627)				
RQC-100*	290	LT	HR plate	136 (938)	130 (896)	155 (1069)	43	0.56	0.06	170 (1172)
RQC-100*	290	L	HR plate	135 (931)	128 (883)	193 (1331)	67	1.02	0.06	170 (1172)
10B62	430	L	Q&T	238 (1641)	219 (1510)	258 (1779)	38	0.89	0.042	260 (1793)
1005–1009	90	LT	HR sheet	52 (359)	39 (269)	104 (717)	73	1.3	0.12	73 (503)
1005–1009	125	LT	CD sheet	68 (469)	65 (448)	108 (745)	66	1.09	0.029	78 (538)
1005–1009	125	L	CD sheet	60 (414)	58 (400)	122 (841)	64	1.02	0.049	76 (524)
1005–1009	90	L	HR sheet	50 (345)	38 (262)	123 (848)	80	1.6	0.16	77 (531)
1015	80	L	Normalized	60 (414)	33 (228)	105 (724)	68	1.14	0.26	
1020	108	L	HR plate plate	64 (441)	38 (262)	103 (710)	62	0.96	0.19	107 (738)
1040	225	L	As forged	90 (621)	50 (345)	152 (1048)	60	0.93	0.22	
1045	225	L	Q&T	105 (724)	92 (634)	178 (1227)	65	1.04	0.13	166 (1145)
1045	410	L	Q&T	210 (1448)	198 (1365)	270 (1862)	51	0.72	0.076	302 (2082)
1045	390	L	Q&T	195 (1344)	185 (1276)	270 (1862)	59	0.89	0.044	
1045	450	L	Q&T	230 (1586)	220 (1517)	305 (2103)	55	0.81	0.041	
1045	500	L	Q&T	265 (1827)	245 (1689)	330 (2275)	51	0.71	0.047	
1045	595	L	Q&T	325 (2241)	270 (1862)	395 (2723)	41	0.52	0.071	
1080 + Mn	326	L	HR plate	162 (1117)	92 (634)	181 (1248)	17	0.17		
1080 + Mn	375	L	Q&T	189 (1303)	166 (1145)	235 (1620)	31	0.37		

TABLE 4.16 Monotonic Stress-Strain Properties of Selected Metals (Sort: Steel, A1, SAE Spec., Increasing True Fracture Strength) (*Continued*)

SAE spec	BHn	Grain dir	Process description	Ultimate strength, ksi (MPa)	Yield strength, ksi (MPa)	True fracture strength, ksi (MPa)	%RA	True fracture ductility	Strain hard'G exponent	Strength coefficient, ksi (MPa)
1080 + Mn	415	L	Q&T	206 (1420)	180 (1241)	243 (1675)	31	0.36		
1080 + Mn	505	L	Q&T	265 (1827)	235 (1620)	295 (2034)	30	0.36		
1080 + Mn	555	L	Q&T	309 (2130)	273 (1882)	339 (2337)	17	0.18		
1144	265	L	CD strain rel	135 (931)	104 (717)	168 (1158)	33	0.51		
1144	305	L	Drawn at temp	150 (1034)	148 (1020)	220 (1517)	25	0.29		
1541F	290	L	Q&T forging	138 (951)	129 (889)	185 (1276)	49	0.68	0.12	
1541F	260	L	Q&T forging	129 (889)	114 (786)	185 (1276)	60	0.93	0.13	
30304	160	L	HR & annealed	108 (745)	37 (255)	228 (1572)	74	1.37		
30304	327	L	CD	138 (951)	108 (745)	246 (1696)	69	1.16		
30310	145	L	HR & annealed	93 (641)	32 (221)	168 (1158)	64	1.01		
4130	258	L	Q&T	130 (896)	113 (779)	206 (1420)	67	1.12		
4130	365	L	Q&T	207 (1427)	197 (1358)	264 (1820)	55	0.79		
4140	310	L	Q&T drawn at temp	156 (1076)	140 (965)	221 (1524)	60	0.69		
4142	310	L	Drawn at temp	154 (1062)	152 (1048)	162 (1117)	29	0.35		
4142	335	L	Drawn at temp	181 (1248)	179 (1234)	246 (1696)	28	0.34		
4142	380	L	Q&T	205 (1413)	200 (1379)	265 (1827)	48	0.66	0.051	
4142	400	L	Q&T and deformed	225 (1551)	210 (1448)	275 (1896)	47	0.63	0.032	
4142	450	L	Q&T	255 (1758)	230 (1586)	290 (1999)	42	0.54	0.043	
4142	475	L	Q&T and deformed	295 (2034)	275 (1896)	300 (2068)	20	0.22	0.01	
4142	450	L	Q&T and deformed	280 (1931)	270 (1862)	305 (2103)	37	0.46	0.016	
4142	475	L	Q&T	280 (1931)	250 (1724)	315 (2172)	35	0.43	0.048	
4142	670	L	As quenched	355 (2448)	235 (1620)	375 (2586)	6	0.06	0.136	
4142	560	L	Q&T	325 (2241)	245 (1689)	385 (2654)	27	0.31	0.091	
4340	243	L	HR & annealed	120 (827)	92 (634)	158 (1089)	43	0.57		
4340	409	L	Q&T	213 (1469)	199 (1372)	226 (1558)	38	0.48		
4340	350	L	Q&T	180 (1241)	170 (1172)	240 (1655)	57	0.84	0.066	229 (1579)
5160	430	L	Q&T	242 (1669)	222 (1531)	280 (1931)	42	0.87	0.055	308 (2124)
52100	518	L	Sol heat Q&T	292 (2013)	279 (1924)	318 (2193)	11	0.12		

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9262	260	L	Annealed	134 (924)	66 (455)	151 (1041)	14	0.16	0.22	253 (1744)
9262	280	L	Q&T	145 (1000)	114 (786)	177 (1220)	33	0.41	0.14	
9262	410	L	Q&T	227 (1565)	200 (1379)	269 (1855)	32	0.38	0.06	283 (1951)
950C	159	LT	HR plate	82 (565)	46 (317)	135 (931)	64	1.03	0.19	134 (924)
950C	150	L	HR bar	82 (565)	47 (324)	145 (1000)	69	1.19	0.21	
950X	150	L	Plate channel	64 (441)	50 (345)	109 (752)	65	1.06	0.16	98 (676)
950X	156	L	HR plate	77 (531)	48 (331)	145 (1000)	72	1.24	0.19	131 (903)
980X	225	L	Plate channel	101 (696)	82 (565)	177 (1220)	68	1.15	0.13	181 (1248)
1100 AI	26	L	As received	16 (110)	14 (97)		88	2.09		
2014-T6	155	L	Sol tr & artif age	74 (510)	67 (462)	87 (600)	25	0.29		
2024-T351		L	Sol tr strn harden	68 (469)	55 (379)	81 (558)	25	0.28	0.032	66 (455)
2024-T4		L	Sol tr & RT age	69 (476)	44 (303)	92 (634)	35	0.43	0.20	117 (807)
5456-H311	95	L	Strain hardened	58 (400)	34 (234)	76 (524)	35	0.42		
7075-T6		L	Sol tr & artif age	84 (579)	68 (469)	108 (745)	33	0.41	0.113	120 (827)

* Trade name—Bethlehem Steel Corp.
† ASTM specification.
‡ Trade name—Armco Steel Corp.
§ Trade name—Republic Steel Corp.
¶ Grade number—Allegheny Ludlum Steel Corp.
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TABLE 4.17 Fundamental Quality Description* of Carbon and Alloy Steels†

Carbon steels			Alloy steels
Semifinished for forging Forging quality Special hardenability Special internal soundness Nonmetallic inclusion requirement Special surface Carbon steel structural sections Structural quality Carbon steel plates Regular quality Structural quality Cold-drawing quality Cold-pressing quality Cold-flanging quality Forging quality Pressure vessel quality Hot-rolled carbon steel bars Merchant quality Special quality Special hardenability Special internal soundness Nonmetallic inclusion requirement Special surface Scrapless nut quality Axle shaft quality Cold-extrusion quality Cold-heading and cold-forging quality	Hot-rolled sheets Commercial quality Drawing quality Drawing quality special killed Structural quality Cold-rolled sheets Commercial quality Drawing quality Drawing quality special killed Structural quality Porcelain enameling sheets Commercial quality Drawing quality Drawing quality special killed Long-terne sheets Commercial quality Drawing quality Drawing quality special killed Structural quality Galvanized sheets Commercial quality Drawing quality Drawing quality special killed Lock forming quality Electrolytic zinc-coated sheets Commercial quality Drawing quality Drawing quality special killed Structural quality	Tin mill products Specific quality descriptions are not applicable to tin mill products. Carbon steel wire Industrial quality wire Cold-extrusion wires Heading, forging, and roll threading wires Mechanical spring wires Upholstery spring construction wires Welding wire Carbon steel flat wire Stitching wire Stapling wire Carbon steel pipe Structural tubing Line pipe Oil country tubular goods Steel specialty tubular products Pressure tubing Mechanical tubing Aircraft tubing Hot-rolled carbon steel wire rods Industrial quality Rods for manufacture of wire intended for electric welded chain Rods for heading, forging, and roll-threading wire	Alloy steel plates Drawing quality Pressure vessel quality Structural quality Aircraft physical quality Hot-rolled alloy steel bars Regular quality Aircraft quality or steel subject to magnetic particle inspection Axle shaft quality Bearing quality Cold-heading quality Special cold-heading quality Rifle barrel quality, gun quality, shell or A.P. shot quality Alloy steel wire Aircraft quality Bearing quality Special surface quality Cold-finished alloy steel bars Regular quality Aircraft quality or steel subject to magnetic particle inspection Axle shaft quality Bearing shaft quality Cold-heading quality Special cold-heading quality Rifle barrel quality, gun quality, shell or A.P. shot quality

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Cold-finished carbon steel bars
- Standard quality
  - Special hardenability
  - Special internal soundness
  - Nonmetallic inclusion requirement
  - Special surface
- Cold-heading and cold-forging quality
- Cold-extrusion quality

Hot-rolled strip
- Commercial quality
- Drawing quality
- Drawing quality special killed
- Structural quality

Cold-rolled strip
- Specific quality descriptions are not provided in cold-rolled strip, since this product is largely produced for specific end use.
- Rods for lock washer wire
- Rods for scrapless nut wire
- Rods for upholstery spring wire
- Rods for welding wire

Line pipe

Oil country tubular goods

Steel specialty tubular goods
- Pressure tubing
- Mechanical tubing
- Stainless and heat-resisting pipe, pressure tubing, and mechanical tubing
- Aircraft tubing
- Pipe

* In the case of certain qualities, phosphorus and sulfur are ordinarily furnished to lower limits than the specified maximum. For details, refer to the appropriate AISI Manual.

† Detailed description of many of the categories listed in this table appear in an appropriate section of the AISI manual.

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TABLE 4.18 Comparison of Tool Steels on the Basis of Properties Affecting Selection

SAE steel designation	Nondeforming properties	Safety in hardening	Depth of hardening*	Toughness	Resistance to softening effect of heat	Wear resistance	Machinability
Water-hardening tool steels							
W108	Poor	Fair	Shallow	Good†	Poor	Fair	Best
W109	Poor	Fair	Shallow	Good†	Poor	Fair	Best
W110	Poor	Fair	Shallow	Good†	Poor	Good	Best
W112	Poor	Fair	Shallow	Good†	Poor	Good	Best
W209	Poor	Fair	Shallow	Good†	Poor	Fair	Best
W210	Poor	Fair	Shallow	Good	Poor	Good	Best
W310	Poor	Fair	Shallow	Good	Poor	Good	Best
Shock-resisting tool steels							
S1—Chromium-tungsten	Fair	Good	Medium	Good	Fair	Fair	Fair
S2—Silicon-molybdenum	W Poor‡ O Fair‡	W Poor‡ O Good‡	Medium	Best	Fair	Fair	Good
S5—Silicon-manganese	W Poor‡ O Fair‡	W Poor‡ O Good‡	Medium	Best	Fair	Fair	Fair
Cold-work tool steels							
Oil-hardening types							
O1—Low manganese	Good	Good	Medium	Fair	Poor	Good	Good
O2—High manganese	Good	Good	Medium	Fair	Poor	Good	Good
O6—Molybdenum graphitic	Fair	Good	Medium	Fair	Poor	Good	Best
Medium-alloy air-hardening types							
A2—5% Chromium air hard	Best	Best	Deep	Fair	Fair	Good	Fair
High-carbon–high-chromium types							
D2—High-carbon–high-chromium (air)	Best	Best	Deep	Fair	Fair	Best	Poor
D3—High-carbon–high-chromium (oil)	Good	Good	Deep	Poor	Fair	Best	Poor
D5—High-carbon–high-chromium-cobalt	Best	Best	Deep	Fair	Fair	Best	Poor
D7—High-carbon–high-chromium–high-vanadium	Best	Best	Deep	Poor	Fair	Best	Poor

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Hot-work tool steels							
Chromium base types							
H11—Chromium-molybdenum-V	Good	Good	Deep	Good	Good	Fair	Fair
H12—Chromium-molybdenum-tungsten	Good	Good	Deep	Good	Good	Fair	Fair
H13—Chromium-molybdenum-VV	Good	Good	Deep	Good	Good	Fair	Fair
Tungsten base types							
H21—Tungsten	Good	Good	Deep	Good	Good	Fair	Fair
High-speed tool steels							
Tungsten base types							
T1—Tungsten 18-4-1	Good	Good	Deep	Poor	Good	Good	Fair
T2—Tungsten 18-4-2	Good	Good	Deep	Poor	Good	Good	Fair
T4—Cobalt-tungsten 18-4-1-5	Good	Fair	Deep	Poor	Best	Good	Fair
T5—Cobalt-tungsten 18-4-2-8	Good	Fair	Deep	Poor	Best	Good	Fair
T8—Cobalt-tungsten 14-4-2-5	Good	Fair	Deep	Poor	Best	Good	Fair
Molybdenum base types							
M1—Molybdenum 8-2-1	Good	Fair	Deep	Poor	Good	Good	Fair
M2—Molybdenum-tungsten 6-6-2	Good	Fair	Deep	Poor	Good	Good	Fair
M3—Molybdenum-tungsten 6-6-3	Good	Fair	Deep	Poor	Good	Best	Fair
M4—Molybdenum-tungsten 6-6-4	Good	Fair	Deep	Poor	Good	Best	Fair
Special-purpose tool steels							
Low-alloy types							
L6—Nickel-chromium	Fair	Good	Medium	Fair	Poor	Fair	Fair
L7—Chromium	Fair	Good	Medium	Fair	Poor	Good	Fair

* These are intended to emphasize major differences between the groups of steels and do not account for the minor differences in depths of hardening that exist between steels of the same group. This is particularly true of the water-hardening W steels which are frequently furnished with varying degrees of hardenability as listed in Table 4.19.

† Toughness decreases somewhat with increasing depth of hardening.

‡ W as shown here indicates water quench. O as shown here indicates oil quench.

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TABLE 4.19 Approximate Comparison of Tool and Die Steels on the Basis of Some Heat-Treating Characteristics

SAE steel designation	Quench medium	Preheat temperature, °F	Hardening temperature range, °F*	Hardness after quenching, Rockwell C	Tempering temperature range, °F*	Hardness after tempering, Rockwell C	Decarburization (prevention of during heat treatment)
Water-hardening tool steel							
W108	Water	—†	1420–1450	65–67	350–525	65–56	—‡
W109	Water	—†	1420–1450	65–67	350–525	65–56	—‡
W110	Water	—†	1420–1450	65–67	350–525	65–56	—‡
W112	Water	—†	1420–1500	65–67	350–525	65–56	—‡
W209	Water	—†	1420–1500	65–67	350–525	65–56	—‡
W210	Water	—†	1420–1500	65–67	350–525	65–56	—‡
W310	Water	—†	1420–1500	65–67	350–525	65–56	—‡
Shock-resisting tool steels							
S1—Chromium-tungsten	Oil	1200–1300	1650–1800	57–59	300–1000	57–45	—§
S2—Silicon-molybdenum	Water	—†	1550–1575	60–62	300–500	60–54	—‡
	Oil	—†	1600–1625	58–60	300–500	58–54	—‡
S5—Silicon-manganese	Water	—†	1550–1600	60–62	300–650	60–54	—‡
	Oil	—†	1600–1675	58–60	300–650	58–54	—‡
Cold-work tool steels							
Oil-hardening types							
O1—Low manganese	Oil	—†	1450–1500	63–65	300–800	62–50	—‡
O2—High manganese	Oil	—†	1420–1450	63–65	375–500	62–57	—‡
O6—Molybdenum graphitic	Oil	—†	1450–1500	63–65	300–800	63–50	—‡
Medium-alloy air-hardening types							
A2—5% Chromium air hard	Air	1200–1300	1725–1775	61–63	400–700	60–57	—§
High-carbon–high-chromium types							
D2—High-carbon–high-chromium	Air	1200–1300	1800–1875	61–63	400–700	60–58	—§
D3—High-carbon–high-chromium	Oil	1200–1300	1750–1800	62–64	400–700	62–58	—§
D5—High-carbon–high-chromium-cobalt	Air	1200–1300	1800–1875	60–62	400–700	59–57	—§
D7—High-carbon–high-chromium–high-vanadium	Air	1200–1300	1850–1950	63–65	300–500 850–1000	65–63 62–58	—§

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Hot-work tool steels							
Chromium base types							
H11—Chromium-molybdenum-V	Air	1450–1500	1825–1875	53–55	1000–1100	51–43	—[§]
H12—Chromium-molybdenum-tungsten	Oil, Air	1450–1500	1800–1900	53–55	1000–1100	51–43	—[§]
H13—Chromium-molybdenum-VV	Air	1400–1450	1825–1875	53–55	1000–1100	51–43	—[§]
Tungsten base types							
H21—Tungsten	Oil, Air	1500–1550	2100–2150	50–52	950–1150	50–47	—[§]
High-speed tool steels							
Tungsten base types							
T1—Tungsten 18-4-1	Oil, air, salt	1500–1550	2300–2375	63–65	1025–1100	65–63	—[§]
T2—Tungsten 18-4-2	Oil, air, salt	1500–1550	2300–2375	63–65	1025–1100	65–63	—[§]
T4—Cobalt-tungsten 18-4-1-5	Oil, air, salt	1500–1550	2300–2375	63–65	1025–1100	65–63	—[§]
T5—Cobalt-tungsten 18-4-2-8	Oil, air, salt	1500–1550	2300–2400	63–65	1050–1100	65–63	—[§]
T8—Cobalt-tungsten 14-4-2-5	Oil, air, salt	1500–1550	2300–2375	63–65	1025–1100	65–63	—[§]
Molybdenum base types							
M1—Molybdenum 8-2-1	Oil, air, salt	1400–1500	2150–2250	63–65	1025–1050	65–63	—[§]
M2—Molybdenum-tungsten 6-6-2	Oil, air, salt	1450–1500	2175–2250	63–65	1025–1075	65–63	—[§]
M3—Molybdenum-tungsten 6-6-3	Oil, air, salt	1450–1500	2150–2225	63–65	1025–1075	65–63	—[§]
M4—Molybdenum-tungsten 6-6-4	Oil, air, salt	1450–1500	2150–2225	63–65	1025–1075	65–63	—[§]
Special-purpose tool steels							
Low-alloy types							
L6—Nickel-chromium	Oil	—[†]	1500–1600	62–64	400–800	62–48	—[‡]
L7—Chromium	Oil	—[†]	1525–1550	63–65	350–500	62–60	—[‡]

[*] The purpose of these columns is to show the usual ranges of temperature employed in hardening and tempering and is not to be used as a specification.

[†] For large tools and tools having intricate sections, preheating at 1050 to 1200°F is recommended.

[‡] Use moderately oxidizing atmosphere in furnace or a suitable neutral salt bath.

[§] Use protective pack from which volatile matter has been removed, carefully balanced neutral salt bath, or atmosphere controlled furnaces. In the latter case, the furnace atmosphere should be in equilibrium with the carbon content of the steel being treated. Furnace atmosphere dew point is considered a reliable method for measuring and controlling this equilibrium.

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TABLE 4.20 Forging, Normalizing, and Annealing Treatments of Tool and Die Steels

SAE steel designation*	Forging†			Normalizing‡		Annealing§			
	Heat slowly to	Start forging at	Do not forge below	Heat slowly to	Hold at	Temperature	Maximum rate of cooling, °F/h	Approximate Brinell hardness	Approximate Rockwell B
Water-hardening tool steels									
W108	1450	1800–1950	1500	1450	1500	1400–1450	75	159–202	84–94
W109	1450	1800–1950	1500	1450	1500	1375–1425	75	159–202	84–94
W110	1450	1800–1900	1500	1450	1550	1400–1450	75	159–202	84–94
W112	1450	1800–1900	1500	1450	1625	1400–1450	75	159–202	84–94
W209	1450	1800–1950	1500	1450	1500	1375–1425	75	159–202	84–94
W210	1450	1800–1900	1500	1450	1550	1400–1450	75	159–202	84–94
W310	1450	1800–1900	1500	1450	1550	1400–1450	75	159–202	84–94
Shock-resisting tool steels									
S1—Chromium-tungsten	1500	1800–2000	1600	Do not normalize		1450–1500	50	192–235	92–99
S2—Silicon-molybdenum	1500	1900–2100	1600	1500	1650	1400–1450	50	192–229	92–98
S5—Silicon-manganese	1500	1900–2050	1600	1500	1600	1400–1450	50	192–229	92–98
Cold-work tool steels									
Oil-hardening types									
O1—Low manganese	1500	1750–1900	1550	1500	1600	1425–1475	50	183–212	90–96
O2—High manganese	1500	1750–1900	1550	1500	1550	1375–1425	50	183–212	90–96
O6—Molybdenum graphitic	1500	1750–1900	1500	1500	1625	1425–1475	20	183–217	90–96
Medium-alloy air-hardening types									
A2—5% Chromium air hard	1600	1850–2000	1650	Do not normalize		1550–1600	40	202–229	94–98
High-carbon–high-chromium types									
D2—High-carbon–high-chromium (air)	1650	1850–2000	1650	Do not normalize		1600–1650	40	207–255	95–102
D3—High-carbon–high-chromium (oil)	1650	1850–2000	1650	Do not normalize		1600–1650	50	212–255	96–102
D5—High-carbon–high-chromium-cobalt	1600	1850–2000	1650	Do not normalize		1600–1650	40	207–255	95–102
D7—High-carbon–high-chromium–high-vanadium	1650	2050–2125	1800	Do not normalize		1600–1650	50	235–262	99–103

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Hot-work tool steels									
Chromium base types									
H11—Chromium-molybdenum-V	1650	1950–2100	1650	Do not normalize		1550–1600	50	192–229	92–98
H12—Chromium-molybdenum-tungsten	1650	1950–2100	1650	Do not normalize		1600–1650	50	192–229	92–98
H13—Chromium-molybdenum-VV	1650	1950–2100	1650	Do not normalize		1550–1600	50	192–229	92–98
Tungsten base types									
H21—Tungsten	1600	2000–2150	1650	Do not normalize		1600–1650	50	202–235	94–99
High-speed tool steels									
Tungsten base types									
T1—Tungsten 18-4-1	1600	1950–2100	1750	Do not normalize		1600–1650	50	217–255	96–102
T2—Tungsten 18-4-2	1600	2000–2150	1750	Do not normalize		1600–1650	50	223–255	97–102
T4—Cobalt-tungsten 18-4-1-5	1600	2000–2150	1750	Do not normalize		1600–1650	50	229–255	98–102
T5—Cobalt-tungsten 18-4-2-8	1600	2000–2150	1800	Do not normalize		1600–1650	50	248–293	102–106
T8—Cobalt-tungsten 14-4-2-5	1600	2000–2150	1750	Do not normalize		1600–1650	50	229–255	98–102
Molybdenum base types									
M1—Molybdenum 8-2-1	1500	1900–2050	1700	Do not normalize		1525–1600	50	207–248	95–102
M2—Molybdenum-tungsten 6-6-2	1500	1950–2100	1700	Do not normalize		1550–1625	50	217–248	96–102
M3—Molybdenum-tungsten 6-6-3	1500	2000–2150	1700	Do not normalize		1550–1625	50	223–255	97–102
M4—Molybdenum-tungsten 6-6-4	1500	2000–2150	1700	Do not normalize		1550–1625	50	229–255	98–102
Special-purpose tool steels									
Low-alloy types									
L6—Nickel-chromium	1500	1800–2000	1600	1550	1650	1400–1450	50	183–212	90–96
L7—Chromium	1500	1800–2000	1550	1550	1650	1450–1500	50	174–212	88–96

* These tool and die steels are the same as those listed in Table 4.18.

† The temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions and the lower side for smaller sections and lighter reductions. As the alloy content of the steel increases, the time of soaking at forging temperature increases proportionately. Likewise, as the alloy content increases, it becomes necessary to cool slowly from the forging temperature. With very high alloy steels, such as high speed or air hardening steels, this slow cooling is imperative in order to prevent cracking and to leave the steel in a semisoft condition. Either furnace cooling or burying in an insulating medium, such as lime, mica, or silocel, is satisfactory.

‡ The length of time the steel is held after being uniformly heated through at the normalizing temperature varies from about 15 min for a small section to about 1 h for large sizes. Cooling from the normalizing temperature is done in still air. The purpose of normalizing after forging is to refine the grain structure and to produce a uniform structure throughout the forging. Normalizing should not be confused with low temperature (about 1200°F) annealing used for the relief of residual stresses resulting from heavy machining, bending, and forming.

§ The annealing temperature is given as a range, the upper limit of which should be used for large sections and the lower limit for smaller sections. The length of time the steel is held after being uniformly heated through at the annealing temperature varies from about 1 h for light sections and small furnace charges of carbon or low alloy steel to about 4 hr for heavy sections and large furnace charges of high alloy steel.

For information on the forging and heat treating of tool steels, see ASM Handbook, 1948 edition, pp. 653–655.

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TABLE 4.21 Approximate Equivalent Hardness Numbers* for Brinell Hardness Numbers† for Steel

Brinell indentation dia, mm	Brinell hardness no.,† 10-mm ball, 3000-kg load: Standard ball	Brinell hardness no.,† 10-mm ball, 3000-kg load: Tungsten-carbide ball	Vickers hardness no.	Rockwell hardness no.†: A-scale, 60-kg load, Brale penetrator	Rockwell hardness no.†: B-scale, 100-kg load, 1.6-mm (1/16-in) dia ball	Rockwell hardness no.†: C-scale, 150-kg load, Brale penetrator	Rockwell hardness no.†: D-scale, 100-kg load, Brale penetrator	Rockwell superficial hardness no., superficial Brale penetrator: 15-N scale, 15-kg load	Rockwell superficial hardness no., superficial Brale penetrator: 30-N scale, 30-kg load	Rockwell superficial hardness no., superficial Brale penetrator: 45-N scale, 45-kg load	Shore scleroscope hardness no.	Tensile strength (approximate) in MPa (1000 psi)	Brinell indentation dia, mm
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	Col. 14
—	—	—	940	85.6	—	68.0	76.9	93.2	84.4	75.4	97	—	—
—	—	—	920	85.3	—	67.5	76.5	93.0	84.0	74.8	96	—	—
—	—	—	900	85.0	—	67.0	76.1	92.9	83.6	74.2	95	—	—
—	—	(767)	880	84.7	—	66.4	75.7	92.7	83.1	73.6	93	—	—
—	—	(757)	860	84.4	—	65.9	75.3	92.5	82.7	73.1	92	—	—
2.25	—	(745)	840	84.1	—	65.3	74.8	92.3	82.2	72.2	91	—	2.25
—	—	(733)	820	83.8	—	64.7	74.3	92.1	81.7	71.8	90	—	—
—	—	(722)	800	83.4	—	64.0	73.8	91.8	81.1	71.0	88	—	—
2.30	—	(712)	—	—	—	—	—	—	—	—	—	—	2.30
—	—	(710)	780	83.0	—	63.3	73.3	91.5	80.4	70.2	87	—	—
—	—	(698)	760	82.6	—	62.5	72.6	91.2	79.7	69.4	86	—	—
—	—	(684)	740	82.2	—	61.8	72.1	91.0	79.1	68.6	—	—	—
2.35	—	(682)	**737**	**82.2**	—	**61.7**	**72.0**	**91.0**	**79.0**	**68.5**	84	—	**2.35**
—	—	(670)	720	81.8	—	61.0	71.5	90.7	78.4	67.7	83	—	—
—	—	(656)	700	81.3	—	60.1	70.8	90.3	77.6	66.7	—	—	—
2.40	—	(653)	**697**	**81.2**	—	**60.0**	**70.7**	**90.2**	**77.5**	**66.5**	81	—	**2.40**
—	—	(647)	690	81.1	—	59.7	70.5	90.1	77.2	66.2	—	—	—
—	—	(638)	680	80.8	—	59.2	70.1	89.8	76.8	65.7	80	—	—
—	—	630	670	80.6	—	58.8	69.8	89.7	76.4	65.3	—	—	—
2.45	—	**627**	**667**	**80.5**	—	**58.7**	**69.7**	**89.6**	**76.3**	**65.1**	79	—	**2.45**
	—	—	**677**	**80.7**	—	**59.1**	**70.0**	**89.8**	**76.8**	**65.7**	—	—	**2.50**
2.50	—	**601**	**640**	**79.8**	—	**57.3**	**68.7**	**89.0**	**75.1**	**63.5**	77	—	

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2.55	—	—	**640**	**79.8**	—	**57.3**	**68.7**	**89.0**	**75.1**	**63.5**	—	—	—	—	**2.55**
	—	—	**615**	**79.1**	—	**56.0**	**67.7**	**88.4**	**73.9**	**62.1**	75	—	—		
2.60	—	—	**607**	**78.8**	—	**55.6**	**67.4**	**88.1**	**73.5**	**61.6**	—	—	—	—	**2.60**
	555	**591**	**591**	**78.4**	—	**54.7**	**66.7**	**87.8**	**72.7**	**60.6**	73	—	2055 (298)		
2.65	—	—	**579**	**78.0**	—	**54.0**	**66.1**	**87.5**	**72.0**	**59.8**	—	—	2015 (292)		**2.65**
	534	**569**	**569**	**77.8**	—	**53.5**	**65.8**	**87.2**	**71.6**	**59.2**	71	—	1985 (288)		
2.70	—	—	**553**	**77.1**	—	**52.5**	**65.0**	**86.7**	**70.7**	**58.0**	—	—	1915 (278)		**2.70**
	514	**547**	**547**	**76.9**	—	**52.1**	**64.7**	**86.5**	**70.3**	**57.6**	70	—	1890 (274)		
2.75	—	(495)	**539**	**76.7**	—	**51.6**	**64.3**	**86.3**	**69.9**	**56.9**	—	—	1855 (269)		**2.75**
	—	—	**530**	**76.4**	—	**51.1**	**63.9**	**86.0**	**69.5**	**56.2**	—	—	1825 (265)		
	495	**528**	**528**	**76.3**	—	**51.0**	**63.8**	**85.9**	**69.4**	**56.1**	68	—	1820 (264)		
2.80	—	(477)	**516**	**75.9**	—	**50.3**	**63.2**	**85.6**	**68.7**	**55.2**	—	—	1780 (258)		**2.80**
	—	—	**508**	**75.6**	—	**49.6**	**62.7**	**85.3**	**68.2**	**54.5**	—	—	1740 (252)		
	477	**508**	**508**	**75.6**	—	**49.6**	**62.7**	**85.3**	**68.2**	**54.5**	66	—	1740 (252)		
2.85	—	(461)	**495**	**75.1**	—	**48.8**	**61.9**	**84.9**	**67.4**	**53.5**	—	—	1680 (244)		**2.85**
	—	—	**491**	**74.9**	—	**48.5**	**61.7**	**84.7**	**67.2**	**53.2**	—	—	1670 (242)		
	461	**491**	**491**	**74.9**	—	**48.5**	**61.7**	**84.7**	**67.2**	**53.2**	65	—	1670 (242)		
2.90	—	**444**	**474**	**74.3**	—	**47.2**	**61.0**	**84.1**	**66.0**	**51.7**	—	—	1595 (231)		**2.90**
	—	—	**472**	**74.2**	—	**47.1**	**60.8**	**84.0**	**65.8**	**51.5**	—	—	1585 (230)		
	444	**472**	**472**	**74.2**	—	**47.1**	**60.8**	**84.0**	**65.8**	**51.5**	63	—	1585 (230)		
2.95	**429**	**429**	**455**	**73.4**	—	**45.7**	**59.7**	**83.4**	**64.6**	**49.9**	61	—	1510 (219)		**2.95**
3.00	**415**	**415**	**440**	**72.8**	—	**44.5**	**58.8**	**82.8**	**63.5**	**48.4**	59	—	1460 (212)		**3.00**
3.05	**401**	**401**	**425**	**72.0**	—	**43.1**	**57.8**	**82.0**	**62.3**	**46.9**	58	—	1390 (202)		**3.05**
3.10	**388**	**388**	**410**	**71.4**	—	**41.8**	**56.8**	**81.4**	**61.1**	**45.3**	56	—	1330 (193)		**3.10**
3.15	**375**	**375**	**396**	**70.6**	—	**40.4**	**55.7**	**80.6**	**59.9**	**43.6**	54	—	1270 (184)		**3.15**
3.20	**363**	**363**	**383**	**70.0**	—	**39.1**	**54.6**	**80.0**	**58.7**	**42.0**	52	—	1220 (177)		**3.20**
3.25	**352**	**352**	**372**	**69.3**	(110.0)	**37.9**	**53.8**	**79.3**	**57.6**	**40.5**	51	—	1180 (171)		**3.25**
3.30	**341**	**341**	**360**	**68.7**	(109.0)	**36.6**	**52.8**	**78.6**	**56.4**	**39.1**	50	—	1130 (164)		**3.30**
3.35	**331**	**331**	**350**	**68.1**	(108.5)	**35.5**	**51.9**	**78.0**	**55.4**	**37.8**	48	—	1095 (159)		**3.35**
3.40	**321**	**321**	**339**	**67.5**	(108.0)	**34.3**	**51.0**	**77.3**	**54.3**	**36.4**	47	—	1060 (154)		**3.40**
3.45	**311**	**311**	**328**	**66.9**	(107.5)	**33.1**	**50.0**	**76.7**	**53.3**	**34.4**	46	—	1025 (149)		**3.45**
3.50	**302**	**302**	**319**	**66.3**	(107.0)	**32.1**	**49.3**	**76.1**	**52.2**	**33.8**	45	—	1005 (146)		**3.50**
3.55	**293**	**293**	**309**	**65.7**	(106.0)	**30.9**	**48.3**	**75.5**	**51.2**	**32.4**	43	—	970 (141)		**3.55**

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TABLE 4.21 Approximate Equivalent Hardness Numbers* for Brinell Hardness Numbers† for Steel (*Continued*)

Brinell indentation dia, mm	Brinell hardness no.,† 10-mm ball, 3000-kg load: Standard ball	Brinell hardness no.,† 10-mm ball, 3000-kg load: Tungsten-carbide ball	Vickers hardness no.	Rockwell hardness no.†: A-scale, 60-kg load, Brale penetrator	Rockwell hardness no.†: B-scale, 100-kg load, 1.6-mm (1/16-in) dia ball	Rockwell hardness no.†: C-scale, 150-kg load, Brale penetrator	Rockwell hardness no.†: D-scale, 100-kg load, Brale penetrator	Rockwell superficial hardness no., superficial Brale penetrator: 15-N scale, 15-kg load	Rockwell superficial hardness no., superficial Brale penetrator: 30-N scale, 30-kg load	Rockwell superficial hardness no., superficial Brale penetrator: 45-N scale, 45-kg load	Shore scleroscope hardness no.	Tensile strength (approximate) in MPa (1000 psi)	Brinell indentation dia, mm
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	Col. 14
3.60	**285**	**285**	**301**	**65.3**	(105.5)	**29.9**	**47.6**	**75.0**	**50.3**	**31.2**	—	950 (138)	**3.60**
3.65	**277**	**277**	**292**	**64.6**	(104.5)	**28.8**	**46.7**	**74.4**	**49.3**	**29.9**	41	925 (134)	**3.65**
3.70	**269**	**269**	**284**	**64.1**	(104.0)	**27.6**	**45.9**	**73.7**	**48.3**	**28.5**	40	895 (130)	**3.70**
3.75	**262**	**262**	**276**	**63.6**	(103.0)	**26.6**	**45.0**	**73.1**	**47.3**	**27.3**	39	875 (127)	**3.75**
3.80	**255**	**255**	**269**	**63.0**	(102.0)	**25.4**	**44.2**	**72.5**	**46.2**	**26.0**	38	850 (123)	**3.80**
3.85	**248**	**248**	**261**	**62.5**	(101.0)	**24.2**	**43.2**	**71.7**	**45.1**	**24.5**	37	825 (120)	**3.85**
3.90	**241**	**241**	**253**	**61.8**	100.0	**22.8**	**42.0**	**70.9**	**43.9**	**22.8**	36	800 (116)	**3.90**
3.95	**235**	**235**	**247**	**61.4**	99.0	**21.7**	**41.4**	**70.3**	**42.9**	**21.5**	35	785 (114)	**3.95**
4.00	**229**	**229**	**241**	**60.8**	98.2	**20.5**	**40.5**	**69.7**	**41.9**	**20.1**	34	765 (111)	**4.00**
4.05	223	223	234	—	97.3	(18.8)	—	—	—	—	—	—	4.05
4.10	217	217	228	—	96.4	(17.5)	—	—	—	—	33	725 (105)	4.10
4.15	212	212	222	—	95.5	(16.0)	—	—	—	—	—	705 (102)	4.15
4.20	207	207	218	—	94.6	(15.2)	—	—	—	—	32	690 (100)	4.20
4.25	201	201	212	—	93.8	(13.8)	—	—	—	—	31	675 (98)	4.25
4.30	197	197	207	—	92.8	(12.7)	—	—	—	—	30	655 (95)	4.30
4.35	192	192	202	—	91.9	(11.5)	—	—	—	—	29	640 (93)	4.35
4.40	187	187	196	—	90.7	(10.0)	—	—	—	—	—	620 (90)	4.40
4.45	183	183	192	—	90.0	(9.0)	—	—	—	—	28	615 (89)	4.45
4.50	179	179	188	—	89.0	(8.0)	—	—	—	—	27	600 (87)	4.50
4.55	174	174	182	—	87.8	(6.4)	—	—	—	—	—	585 (85)	4.55
4.60	170	170	178	—	86.8	(5.4)	—	—	—	—	26	570 (83)	4.60
4.65	167	167	175	—	86.0	(4.4)	—	—	—	—	—	560 (81)	4.65
4.70	163	163	171	—	85.0	(3.3)	—	—	—	—	25	545 (79)	4.70

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4.80	156	156	163	—	82.9	(0.9)	—	—	—	—	—	525 (76)	4.80
4.90	149	149	156	—	80.8	—	—	—	—	—	23	505 (73)	4.90
5.00	143	143	150	—	78.7	—	—	—	—	—	22	490 (71)	5.00
5.10	137	137	143	—	76.4	—	—	—	—	—	21	460 (67)	5.10
5.20	131	131	137	—	74.0	—	—	—	—	—	—	450 (65)	5.20
5.30	126	126	132	—	72.0	—	—	—	—	—	20	435 (63)	5.30
5.40	121	121	127	—	69.8	—	—	—	—	—	19	415 (60)	5.40
5.50	116	116	122	—	67.6	—	—	—	—	—	18	400 (58)	5.50
5.60	111	111	117	—	65.7	—	—	—	—	—	15	385 (56)	5.60

* This table corresponds to the table in ASM Metals Handbook, 8th Edition, Vol. 1, page 1235. It has been modified to add metric equivalents for approximate tensile strength values and to indicate Brinell hardness values that are beyond the recommended range for this test.

† Values in ( ) are beyond normal range and are given for information only.

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TABLE 4.22 Approximate Equivalent Hardness Numbers* for Rockwell C Hardness Numbers for Steel

Rockwell C-scale hardness no.†	Vickers hardness no.	Brinell hardness no.,† 10-mm ball, 3000-kg load		Rockwell hardness no.†			Rockwell superficial hardness no., superficial Brale penetrator			Shore scleroscope hardness no.	Tensile strength (approximate) in MPa (1000 psi)	Rockwell C-scale hardness no.†
		Standard ball	Tungsten-carbide ball	A-scale, 60-kg load, Brale penetrator	B-scale, 100-kg load, 1.6-mm (1/16-in) dia ball	D-scale, 100-kg load, Brale penetrator	15-N scale, 15-kg load	30-N scale, 30-kg load	45-N scale, 45-kg load			
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13
68	**940**	—	—	**85.6**	—	**76.9**	**93.2**	**84.4**	**75.4**	97	—	**68**
67	**900**	—	—	**85.0**	—	**76.1**	**92.9**	**83.6**	**74.2**	95	—	**67**
66	**865**	—	—	**84.5**	—	**75.4**	**92.5**	**82.8**	**73.3**	92	—	**66**
65	**832**	—	(739)	**83.9**	—	**74.5**	**92.2**	**81.9**	**72.0**	91	—	**65**
64	**800**	—	(722)	**83.4**	—	**73.8**	**91.8**	**81.1**	**71.0**	88	—	**64**
63	**772**	—	(705)	**82.8**	—	**73.0**	**91.4**	**80.1**	**69.9**	87	—	**63**
62	**746**	—	(688)	**82.3**	—	**72.2**	**91.1**	**79.3**	**68.8**	85	—	**62**
61	**720**	—	(670)	**81.8**	—	**71.5**	**90.7**	**78.4**	**67.7**	83	—	**61**
60	**697**	—	(654)	**81.2**	—	**70.7**	**90.2**	**77.5**	**66.6**	81	—	**60**
59	**674**	—	(634)	**80.7**	—	**69.9**	**89.8**	**76.6**	**65.5**	80	—	**59**
58	**653**	—	**615**	**80.1**	—	**69.2**	**89.3**	**75.7**	**64.3**	78	—	**58**
57	**633**	—	**595**	**79.6**	—	**68.5**	**88.9**	**74.8**	**63.2**	76	—	**57**
56	**613**	—	**577**	**79.0**	—	**67.7**	**88.3**	**73.9**	**62.0**	75	—	**56**
55	**595**	—	**560**	**78.5**	—	**66.9**	**87.9**	**73.0**	**60.9**	74	2075 (301)	**55**
54	**577**	—	**543**	**78.0**	—	**66.1**	**87.4**	**72.0**	**59.8**	72	2015 (292)	**54**
53	**560**	—	**525**	**77.4**	—	**65.4**	**86.9**	**71.2**	**58.6**	71	1950 (283)	**53**
52	**544**	(500)	**512**	**76.8**	—	**64.6**	**86.4**	**70.2**	**57.4**	69	1880 (273)	**52**
51	**528**	(487)	**496**	**76.3**	—	**63.8**	**85.9**	**69.4**	**56.1**	68	1820 (264)	**51**
50	**513**	(475)	**481**	**75.9**	—	**63.1**	**85.5**	**68.5**	**55.0**	67	1760 (255)	**50**
49	**498**	(464)	**469**	**75.2**	—	**62.1**	**85.0**	**67.6**	**53.8**	66	1695 (246)	**49**
48	**484**	**451**	**455**	**74.7**	—	**61.4**	**84.5**	**66.7**	**52.5**	64	1635 (237)	**48**
47	**471**	**442**	**443**	**74.1**	—	**60.8**	**83.9**	**65.8**	**51.4**	63	1580 (229)	**47**
46	**458**	**432**	**432**	**73.6**	—	**60.0**	**83.5**	**64.8**	**50.3**	62	1530 (222)	**46**
45	**446**	**421**	**421**	**73.1**	—	**59.2**	**83.0**	**64.0**	**49.0**	60	1480 (215)	**45**
44	**434**	**409**	**409**	**72.5**	—	**58.5**	**82.5**	**63.1**	**47.8**	58	1435 (208)	**44**

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43	**423**	**400**	**400**	**72.0**	—	**57.7**	**82.0**	**62.2**	**46.7**	57	1385 (201)	**43**
42	**412**	**390**	**390**	**71.5**	—	**56.9**	**81.5**	**61.3**	**45.5**	56	1340 (194)	**42**
41	**402**	**381**	**381**	**70.9**	—	**56.2**	**80.9**	**60.4**	**44.3**	55	1295 (188)	**41**
40	**392**	**371**	**371**	**70.4**	—	**55.4**	**80.4**	**59.5**	**43.1**	54	1250 (181)	**40**
39	**382**	**362**	**362**	**69.9**	—	**54.6**	**79.9**	**58.6**	**41.9**	52	1215 (176)	**39**
38	**372**	**353**	**353**	**69.4**	—	**53.8**	**79.4**	**57.7**	**40.8**	51	1180 (171)	**38**
37	**363**	**344**	**344**	**68.9**	—	**53.1**	**78.8**	**56.8**	**39.6**	50	1160 (168)	**37**
36	**354**	**336**	**336**	**68.4**	(109.0)	**52.3**	**78.3**	**55.9**	**38.4**	49	1115 (162)	**36**
35	**345**	**327**	**327**	**67.9**	(108.5)	**51.5**	**77.7**	**55.0**	**37.2**	48	1080 (157)	**35**
34	**336**	**319**	**319**	**67.4**	(108.0)	**50.8**	**77.2**	**54.2**	**36.1**	47	1055 (153)	**34**
33	**327**	**311**	**311**	**66.8**	(107.5)	**50.0**	**76.6**	**53.3**	**34.9**	46	1025 (149)	**33**
32	**318**	**301**	**301**	**66.3**	(107.0)	**49.2**	**76.1**	**52.1**	**33.7**	44	1000 (145)	**32**
31	**310**	**294**	**294**	**65.8**	(106.0)	**48.4**	**75.6**	**51.3**	**32.5**	43	980 (142)	**31**
30	**302**	**286**	**286**	**65.3**	(105.5)	**47.7**	**75.0**	**50.4**	**31.3**	42	950 (138)	**30**
29	**294**	**279**	**279**	**64.7**	(104.5)	**47.0**	**74.5**	**49.5**	**30.1**	41	930 (135)	**29**
28	**286**	**271**	**271**	**64.3**	(104.0)	**46.1**	**73.9**	**48.6**	**28.9**	41	910 (132)	**28**
27	**279**	**264**	**264**	**63.8**	(103.0)	**45.2**	**73.3**	**47.7**	**27.8**	40	880 (128)	**27**
26	**272**	**258**	**258**	**63.3**	(102.5)	**44.6**	**72.8**	**46.8**	**26.7**	38	860 (125)	**26**
25	**266**	**253**	**253**	**62.8**	(101.5)	**43.8**	**72.2**	**45.9**	**25.5**	38	840 (122)	**25**
24	**260**	**247**	**247**	**62.4**	(101.0)	**43.1**	**71.6**	**45.0**	**24.3**	37	825 (120)	**24**
23	**254**	**243**	**243**	**62.0**	100.0	**42.1**	**71.0**	**44.0**	**23.1**	36	805 (117)	**23**
22	**248**	**237**	**237**	**61.5**	99.0	**41.6**	**70.5**	**43.2**	**22.0**	35	785 (114)	**22**
21	**243**	**231**	**231**	**61.0**	98.5	**40.9**	**69.9**	**42.3**	**20.7**	35	770 (112)	**21**
20	**238**	**226**	**226**	**60.5**	97.8	**40.1**	**69.4**	**41.5**	**19.6**	34	760 (110)	**20**
(18)	230	219	219	—	96.7	—	—	—	—	33	730 (106)	(18)
(16)	222	212	212	—	95.5	—	—	—	—	32	705 (102)	(16)
(14)	213	203	203	—	93.9	—	—	—	—	31	675 (98)	(14)
(12)	204	194	194	—	92.3	—	—	—	—	29	650 (94)	(12)
(10)	196	187	187	—	90.7	—	—	—	—	28	620 (90)	(10)
(8)	188	179	179	—	89.5	—	—	—	—	27	600 (87)	(8)
(6)	180	171	171	—	87.1	—	—	—	—	26	580 (84)	(6)
(4)	173	165	165	—	85.5	—	—	—	—	25	550 (80)	(4)
(2)	166	158	158	—	83.5	—	—	—	—	24	530 (77)	(2)
(0)	160	152	152	—	81.7	—	—	—	—	24	515 (75)	(0)

* The values in this table shown in **boldface type** correspond to the values shown in the corresponding joint SAE-ASM-ASTM Committee on Hardness Conversions as printed in ASTM E 140, Table 1.

† Values in ( ) are beyond normal range and are given for information only.

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Carbon and alloy steels: Uses by SAE/AISI number

SAE/AISI 1006 through 1015. Low-carbon, high-formability, weldable. Used for sheet metal, strip, wire, and rod. Excellent drawing qualities. Low-strength applications. Sheet metal structures, body and fender work, deep-drawing parts of sheet steel.

SAE/AISI 1016 through 1030. Increased strength over the low-carbon group. These are known as the *case-hardening* or *carburizing grades.* The higher-manganese grades machine well. The higher-carbon types are used for thicker sections where a stronger core is desired. Type 1018 is used for a great many applications, may be easily case-hardened, and is readily available. Grades 1020 and 1025 are used for low-strength bolts. All these steels are readily welded.

SAE/AISI 1030 through 1052. These are the medium-carbon types of steels used where higher strength than the lower-carbon grades is required. All these steels are used for forgings. Axles and shafts are made from the 1038 to 1045 group. Widely used for machined parts, both heat-treated and non-heat-treated. Welding is possible with precautions taken during the cooling process.

SAE/AISI 1055 through 1095. These are the high-carbon grades of carbon steel. Used for flat stampings, spring wire, cutting tools, flat springs, and many other high-strength applications. These steels are usually heat-treated for their particular application and provide excellent wear resistance. Not recommended for welding applications.

Specific applications

SAE/AISI 1018. Low-carbon, medium-manganese steel. Quality bar for carburized parts: gears, shafts, bolts, pins, etc.

SAE/AISI 1035. Medium-carbon, special-quality steel used for bolts, nuts, shafts, pins, etc. Can be heat-treated.

SAE/AISI 1045. Medium-carbon, special-quality steel used for shafts, axles, gears, splines, etc. Can be heat-treated.

SAE/AISI 12L14. Low-carbon, resulfurized, rephosphorized, and leaded steel used for screw-machine parts such as studs, nuts, and various fasteners. Can be case-hardened.

SAE/AISI 1215. Similar to 12L14 and low-carbon steel used for studs, nuts, and fasteners. Can be case-hardened.

SAE/AISI 12L15. Leaded version of 1215 used for screw-machine parts. Can be case-hardened.

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SAE/AISI 1117. Low-carbon, resulfurized, free-cutting steel used for shafts, gears, pins, nuts, etc. Can be carburized.

SAE/AISI 11L17. Leaded version of 1117 used for screw-machine parts, gears, shafts, pins, etc. Can be carburized.

SAE/AISI 1141. Medium-carbon, resulfurized, free-cutting steel used for shafts, nuts, bolts, etc. Can be hardened by heat treatment.

SAE/AISI 4140. Medium-carbon chromium-molybdenum alloy steel used for studs, nuts, bolts, gears, wrenches, shafts, etc. Can be heat-treated.

SAE/AlSI 41L40. Leaded version of 4140, free-machining type. Can be heat-treated.

SAE/AISI 4145. Medium-carbon chromium-molybdenum steel used for studs, nuts, shafts, wrenches, gears, bolts, etc. Can be heat-treated.

SAE/AISI 41L45. Leaded version of 4145, free-machining type. Can be heat-treated.

SAE/AISI 4620. Low-carbon nickel-molybdenum steel used for gears, cams, pinions, and shafts. Excellent carburizing grade.

SAE/AISI 46L20. Leaded version of 4620, free-machining type. Can be carburized.

SAE/AISI 8620. Low-carbon nickel-chromium-molybdenum alloy steel used for gears, cams, shafts, and pinions. Excellent carburizing grade.

SAE/AISI 86L20. Leaded version of 8620, free-machining type. Can be carburized.

SAE/AISI 4340. Medium-carbon nickel-chromium-molybdenum alloy steel used for gears and shafting. Has high hardenability.

SAE/AISI 8642. Similar to 4340. Has high hardenability.

EF 4130. Aircraft-quality alloy steel.

EF 4140. Aircraft-quality alloy steel.

E 4340, EF 4620, EF 8740, and E 9310. All aircraft-quality alloy steels.

Rather than going into a lengthy description of all the characteristics and heat-treating properties of all the various grades of carbon and alloy steels, the preceding tables can be used by the engineer or designer to determine strength, ductility, hardness, and heat-treatment temperatures for each SAE/AISI and ASTM steel listed. A metallurgist should be consulted prior to making a final design choice about the various steels used in important or critical applications.

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Stainless steels: Uses by AISI number

Note: The stainless steels listed in the preceding tables typically are known by their three-digit SAE numbers, such as 201, 302, 304, 440, etc. The last three digits of the listed SAE numbers are the standard industry identification numbers and are used as such in the following usage summary.

Chromium-nickel stainless steels (austenitic)

201. Low nickel, good corrosion resistance. High work-hardening rate. Excellent weldability.

202. General-purpose type equivalent to 302.

203 EZ. Superior machinability. Good corrosion resistance.

216. Most corrosion resistant of all chromium-nickel-manganese stainless steels.

301. High work-hardening rate. Used in structural applications where high strength and resistance to atmospheric corrosion are required.

302. General-purpose stainless steel with good strength properties. Resistant to many corrosive conditions.

303. Free-machining type used in corrosive atmospheres, strong chemical solutions, many organic chemicals, most dyes, nitric acid, and foods.

303 Pb. Leaded version of 303 used for high-volume automatic machining operations.

304. Low-carbon variation of 302. Weldable with caution. Excellent resistance to a high number of corrosive conditions and chemicals.

304 L. Extra-low-carbon version of 304. Low carbon content prevents carbide precipitation during welding, which can produce cracks at the weld joints. Excellent weldability.

305. Good fabrication stainless for spinning, deep-drawing, and cold-heading operations.

309. Used in high-temperature applications. Resistant to most acids.

310. Higher alloy content improves the basic characteristics. Improved over 309 and 304 for corrosion resistance.

316. Best corrosion resistance of the standard stainless steels. Resists pitting and most chemicals. Used for paper-mill machinery parts and photographic industry parts and containers. High-temperature strength.

316 L. Low-carbon version of 316 that is welded more easily without carbide precipitation.

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317. Higher alloy content than 316, providing more corrosion resistance.

321. This alloy is stabilized with titanium for weldments subject to severe corrosion. Excellent corrosion resistance to a wide variety of organic and inorganic substances.

347. Stabilized with Cb and Ta for use in the carbide precipitation range of 800 to 1500°F, with no impairment to corrosion resistance.

Chromium stainless steels (ferritic)

409. Developed for automotive muffler service and used in noncritical exterior parts. Economical and easily fabricated.

430. Most widely used of the nonhardenable types of chromium stainless steel. Good mechanical properties and heat resistance. Resistant to nitric acid, sulfur gases, and many organic chemicals, including foods.

430 F. Free-machining version of 430. Similar in properties to 430.

446. High resistance to corrosion and scaling at high temperatures. Excellent in sulfuric atmospheres.

Chromium stainless steels (martensitic)

403. Excellent for highly stressed parts such as turbine blades. Good resistance to water and atmospheric corrosion.

405. Variation of 410 for improved weldability. Same corrosion resistance as 403.

410. Low-cost general-purpose stainless steel that is heat-treatable. Used where corrosion is not severe.

410 S. Same as 410 except lower carbon range for improved weldability.

414. Modification of 410 with more nickel to improve corrosion resistance. Can be heat-treated to Rockwell C 25 to C 43.

416. Free-machining version of 410 with corrosion resistance to food acids, basic salts, water, and most atmospheric corrosion products.

440 A, B, C, and F. Series of high-carbon stainless steels. All are the same basic composition except carbon content. Can be heat-treated for high strength and high hardness. These steels are corrosion resistant only in the hardened conditions. 440 F is a free-machining type used in many applications.

Low-chromium stainless steels

PH13-8Mo

15-5PH

PH15-7Mo

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17-4PH

17-7PH

All these grades provide excellent corrosion resistance similar to the austenitic stainless steels and are capable of being heat-treated to various high-strength conditions with minimum distortion. They are generally furnished in the annealed condition for ease of machining. They develop their high-strength properties by aging at selected temperatures. They may be provided as vacuum arc-remelted steels for more demanding applications. They are used in many high-strength, anticorrosion applications. Among other uses, 17-7PH (ASTM A313) round wire is used for helical spring applications, and 17-7PH (ASTM A693) strip is used for flat spring applications.

Tool steels: SAE designations. Refer to Tables 4.17 through 4.19 for physical properties and heat-treating procedures. Also see Chap. 8.

4.1.3 High-strength, low-alloy (HSLA) steels

Typical HSLA steels, with data indicating their mechanical properties, are shown in Table 4.23. Although these are low-alloy grades of steel, they have excellent tensile strength and other properties, making them valuable in many applications. HSLA steels were developed more than 75 years ago by Krupp in Germany. Some of the older German ordnance steels could be classified as modern HSLA steels, and they also were copper-bearing to improve their resistance to atmospheric corrosion. The famous Mauser M1898 rifles produced for various South American countries had bare polished-metal receivers and bolts.

Many of the HSLA steels rely on carbon, manganese, and silicon contents to achieve the strengths associated with these special materials. Other alloying elements such as nickel, chromium, and copper are also present in some of these steels.

4.1.4 Ultra-high-strength steels

Structural steels with very high tensile strengths are referred to as ultra-high-strength steels. An arbitrary minimum yield strength level of 200 ksi has been established for these grades of steels. (Some ultra-high-strength steels fall below this arbitrary minimum.) Tables 4.24 through 4.30 give the mechanical properties of

(Text continued on page 164.)

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TABLE 4.23 Mechanical Properties of HSLA Steel Grades Described in ASTM Specifications

ASTM specification	Type, grade, or condition	UNS designation	Min tensile strength		Min yield strength		Min elongation, %	
			MPa	ksi	MPa	ksi	In 200 mm or 8 in	In 50 mm or 2 in
A242	Type 1	K11510	435 to 480	63 to 70	290 to 345	42 to 50	18	21
	Type 2	K12010	435 to 480	63 to 70	290 to 345	42 to 50	18	21
A440	—	K12810	435 to 485	63 to 70	290 to 345	42 to 50	18	21
A441	—	K12211	415 to 485	60 to 70	275 to 345	40 to 50	18	21
A572	Grade 42	—	415	60	290	42	20	24
	Grade 45	—	415	60	310	45	19	22
	Grade 50	—	450	65	345	50	18	21
	Grade 55	—	485	70	380	55	17	20
	Grade 60	—	520	75	415	60	16	18
	Grade 65	—	550	80	450	65	15	17
A588	Grades A to J	—	435 to 485	63 to 70	290 to 345	42 to 50	18	21
A606	Hot rolled	—	480	70	345	50	—	22
	Hot rolled and annealed or normalized	—	450	65	310	45	—	22
	Cold rolled	—	450	65	310	45	—	22
A607	Grade 45	—	410	60	310	45	—	22 to 25
	Grade 50	—	450	65	345	50	—	20 to 22
	Grade 55	—	480	70	380	55	—	18 to 20
	Grade 60	—	520	75	415	60	—	16 to 18
	Grade 65	—	550	80	450	65	—	15 to 16
	Grade 70	—	590	85	485	70	—	14
A618	Grade I	K02601	483	70	345	50	19	22
	Grade II	K12609	483	70	345	50	18	22
	Grade III	K12700	448	65	345	50	18	20

TABLE 4.23 Mechanical Properties of HSLA Steel Grades Described in ASTM Specifications (*Continued*)

ASTM specification	Type, grade, or condition	UNS designation	Min tensile strength		Min yield strength		Min elongation, %	
			MPa	ksi	MPa	ksi	In 200 mm or 8 in	In 50 mm or 2 in
A633	Grades A and B	—	430 to 570	63 to 83	290	42	18	23
	Grades C and D	—	450 to 620	65 to 90	315 to 345	46 to 50	18	23
	Grade E	K12202	520 to 690	75 to 100	380 to 415	55 to 60	18	23
A656	Grades 1 and 2	(e)	655 to 793	95 to 115	552	80	12	—
A690	—	K12249	485	70	345	50	18	—
A715	Grade 50	—	415	60	345	50	—	22 to 24
	Grade 60	—	485	70	415	60	—	20 to 22
	Grade 70	—	550	80	485	70	—	18 to 20
	Grade 80	—	620	90	550	80	—	16 to 18

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TABLE 4.24 Typical Mechanical Properties of Heat-Treated 4130 Steel

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm or 2 in, %	Reduction in area, %	Hardness, HB	Izod impact energy	
°C	°F	MPa	ksi	MPa	ksi				J	ft · lb
Water-quenched and tempered*										
205	400	1765	256	1520	220	10.0	33.0	475	18	13
260	500	1670	242	1430	208	11.5	37.0	455	14	10
315	600	1570	228	1340	195	13.0	41.0	425	14	10
370	700	1475	214	1250	182	15.0	45.0	400	20	15
425	800	1380	200	1170	170	16.5	49.0	375	34	25
540	1000	1170	170	1000	145	20.0	56.0	325	81	60
650	1200	965	140	830	120	22.0	63.0	270	135	100
Oil-quenched and tempered†										
205	400	1550	225	1340	195	11.0	38.0	450	—	—
260	500	1500	218	1275	185	11.5	40.0	440	—	—
315	600	1420	206	1210	175	12.5	43.0	418	—	—
370	700	1320	192	1120	162	14.5	48.0	385	—	—
425	800	1230	178	1030	150	16.5	54.0	360	—	—
540	1000	1030	150	840	122	20.0	60.0	305	—	—
650	1200	830	120	670	97	24.0	67.0	250	—	—

* 25-mm (1-in) dia round bars quenched from 845 to 870°C (1550 to 1600°F).
† 25-mm (1-in) dia round bars quenched from 860°C (1575°F).

TABLE 4.25 Typical Mechanical Properties of Heat-Treated 4140 Steel*

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm or 2 in, %	Reduction in area, %	Hardness, HB	Izod impact energy	
°C	°F	MPa	ksi	MPa	ksi				J	ft · lb
205	400	1965	285	1740	252	11.0	42	578	15	11
260	500	1860	270	1650	240	11.0	44	534	11	8
315	600	1720	250	1570	228	11.5	46	495	9	7
370	700	1590	231	1460	212	12.5	48	461	15	11
425	800	1450	210	1340	195	15.0	50	429	28	21
480	900	1300	188	1210	175	16.0	52	388	46	34
540	1000	1150	167	1050	152	17.5	55	341	65	48
595	1100	1020	148	910	132	19.0	58	311	93	69
650	1200	900	130	790	114	21.0	61	277	112	83
705	1300	810	117	690	100	23.0	65	235	136	100

* 12.7-mm (0.5-in) dia round bars, oil-quenched from 845°C (1550°F).

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TABLE 4.26 Typical Mechanical Properties of 4340 Steel*

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm or 2 in, %	Reduction in area, %	Hardness		Izod impact energy	
°C	°F	MPa	ksi	MPa	ksi			HB	HRC	J	ft · lb
205	400	1980	287	1860	270	11	39	520	53	20	15
315	600	1760	255	1620	235	12	44	490	49.5	14	10
425	800	1500	217	1365	198	14	48	440	46	16	12
540	1000	1240	180	1160	168	17	53	360	39	47	35
650	1200	1020	148	860	125	20	60	290	31	100	74
705	1300	860	125	740	108	23	63	250	24	102	75

* Oil-quenched from 845°C (1550°F) and tempered at various temperatures.

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TABLE 4.27 Room-Temperature Mechanical Properties of Heat-Treated 6150 Steel

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm or 2 in, %	Reduction in area, %	Hardness, HB	Izod impact energy	
°C	°F	MPa	ksi	MPa	ksi				J	ft · lb
Round bars, 14 mm (0.55 in) in dia*										
205	400	2050	298	1810	263	1	5	610	—	—
260	500	2070	300	1810	263	4	12	570	—	—
315	600	1950	283	1720	250	7	27	540	—	—
370	700	1770	257	1620	235	10	37	505	9	7
425	800	1585	230	1490	216	11	42	470	14	10
480	900	1410	204	1340	195	12	44	420	16	12
540	1000	1250	182	1210	175	13	46	380	20	15
595	1100	1150	167	1080	157	16	47	350	28	21
Round bars, 25 mm (1 in) in dia†										
425	800	1570	228	1450	210	10	37	461	—	—
480	900	1360	197	1210	175	11	41	401	—	—
540	1000	1180	171	1030	150	12	45	341	—	—
595	1100	1030	150	875	127	15	50	302	—	—
650	1200	920	133	760	110	19	55	262	—	—
705	1300	810	118	660	96	23	61	235	—	—

* Normalized at 870°C (1600°F). Oil-quenched from 860°C (1575°F) and tempered at various temperatures.
† Oil-quenched from 860°C and tempered at various temperatures.

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TABLE 4.28 Typical Room-Temperature Mechanical Properties of 8640 Steel

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm or 2 in, %	Reduction in area, %	Impact energy		Hardness	
°C	°F	MPa	ksi	MPa	ksi			J	ft · lb	HB	HRC
Round bars, 13.5 mm (0.53 in) in dia*											
205	400	1810	263	1670	242	8.0	25.8	11.5†	8.5†	555	55
315	600	1585	230	1430	208	9.0	37.3	15.6†	11.5†	461	48
425	800	1380	200	1230	179	10.5	46.3	27.8†	20.5†	415	44
540	1000	1170	170	1050	152	14.0	53.3	56.3†	41.5†	341	37
650	1200	870	126	760	110	20.5	61.0	96.9†	71.5†	269	28
Round bars, 25 mm (1 in.) in dia*											
425	800	1382	200.5	1230	179	10	46	27‡	20‡	415	44
480	900	1250	181	1120	162	13	51	41‡	30‡	388	42
540	1000	1070	155	940	137	17	56	54‡	40‡	331	36
595	1100	1020	148	910	132	16	57	73‡	54‡	302	32
650	1200	865	125.5	760	110.5	20	61	83‡	61‡	269	28

* Oil-quenched from 830°C (1525°F) and tempered at indicated temperature.
† Izod.
‡ Charpy V-notch.

TABLE 4.29 Typical Longitudinal Mechanical Properties of H11 Mod Steel*

Tempering temperature		Tensile strength		Yield strength		Elongation in 50 mm or 2 in, %	Reduction in area, %	Charpy V-notch impact energy		Hardness, HRC
°C	°F	MPa	ksi	MPa	ksi			J	ft · lb	
510	950	2120	308	1710	248	5.9	29.5	13.6	10.0	56.5
540	1000	2010	291	1675	243	9.6	30.6	21.0	15.5	56.0
565	1050	1850	269	1565	227	11.0	34.5	26.4	19.5	52.0
595	1100	1540	223	1320	192	13.1	39.3	31.2	23.0	45.0
650	1200	1060	154	850	124	14.1	41.2	40.0	29.5	33.0
705	1300	940	136	700	101	16.4	42.2	90.6	66.8	29.0

* Air-cooled from 1010°C (1850°F) and double-tempered, 2 + 2 h at indicated temperature.

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TABLE 4.30 Typical Longitudinal Room-Temperature Mechanical Properties of H13 Steel*

Tempering temperature		Tensile strength		Yield strength		Elongation in 4 *D*, %	Reduction in area, %	Charpy V-notch impact energy		Hardness, HRC
°C	°F	MPa	ksi	MPa	ksi			J	ft · lb	
527	980	1960	284	1570	228	13.0	46.2	16	12	52
555	1030	1835	266	1530	222	13.1	50.1	24	18	50
575	1065	1730	251	1470	213	13.5	52.4	27	20	48
593	1100	1580	229	1365	198	14.4	53.7	28.5	21	46
605	1120	1495	217	1290	187	15.4	54.0	30	22	44

* Round bars, oil-quenched from 1010°C (1850°F) and double tempered, 2 + 2 h at indicated temperature.

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some ultra-high-strength steels. Many of these are considered high-quality specialty steels, with 4340 being used as the reference by which all other types of ultra-high-strength steels are measured. AISI type 4340 is used in critical applications, such as key components for aerospace vehicles and commercial and military aircraft.

4.2 Aluminum and Aluminum Alloys

Aluminum and its alloys are among the most used metallic materials, with countless applications and an extremely broad range of physical and chemical properties. Pure aluminum is a silvery white metal, light in weight, nontoxic, and easily cast, forged, and machined. The pure metal was first isolated in the laboratory in 1827. The method of extracting the metal by electrolysis of alumina dissolved in cryolite was discovered by Hall in 1886 in the United States. This method is still in use today and is known as the *Hall process*. Aluminum in its natural forms is the third most abundant material in the earth's crust, exceeded only by oxygen and silicon.

Aluminum alloys are mandatory in many design applications of modern technologies. Many of the modern aluminum alloys are stronger than some steels on a volume basis and weigh only 34 percent (or one-third) as much as steel. The average density of aluminum alloys is 0.098 lb/in^3 and that of steel is 0.282 lb/in^3. The electrical conductivity of aluminum is 60 percent that of an equal cross-sectional area of copper, which is the second best conductor of electric current. In order of electrical conductivity, the best four elements are silver, copper, gold, and aluminum, respectively.

Tables 4.31 through 4.38 show the physical properties of all the present aluminum alloys. Also included are the typical uses for all the wrought and cast types of aluminum alloys in use today. Figure 4.2 shows part of the SAE standard delineating alloy and temper designation systems for aluminum.

4.3 Copper and Copper Alloys

Copper and copper alloys are also among the most important and most used metallic materials. Almost all electrical components and electrical products contain parts made of copper or one or more of its

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important alloys. All the electrical industries worldwide depend on copper and copper alloys. Many new copper alloys have been developed over the past 30 or 40 years, with beryllium-copper alloys as one of the preferred materials in many electrical applications as a replacement for the phosphor bronzes. The phosphor, silicon, and manganese bronzes have many applications where strength and current-carrying ability, combined with corrosion resistance and nonmagnetic properties, are desired. Springs with a high fatigue-endurance limit and good electrical properties are made from the beryllium-copper alloys.

One of the most important uses for copper is in the electrical power distribution industries, where ETP no. 110 copper bus conductors are used to carry the electrical power for all electrical applications. The power distribution industries use such equipment as transformers, power stations, power transmission lines, and electrical switch gear and control equipment. The electric motor industries are another large user of copper products.

Copper is one of the most important elements, with a specific gravity of 8.96 g/cm^3 and weight of 0.324 lb/in^3. It is the second-best conductor of electric current, exceeded only by silver. The copper metal is smelted from oxide, sulfide, and carbonate compounds that are found in their natural states as cuprite, malachite, azurite, and bornite. The most important compounds are the oxides and the sulfates (blue vitriol), the latter being used for agricultural poisons and water purification.

Tables 4.39 through 4.42 list the properties and uses for the many alloys of copper. Table 4.43 lists the standard specifications for brass sheet, strip, plate, and rolled bar (ASTM B-36). Table 4.44 lists the standard specifications for phosphor bronze plate, sheet, strip, and rolled bar (ASTM B-103). Tables 4.45 through 4.47 list the standard specifications for beryllium-copper sheet, plate, strip, and rolled bar (ASTM B-194). Table 4.48 presents the ASTM classification of coppers.

4.4 Magnesium Alloys

Magnesium and magnesium alloys have many applications where moderate strength and light weight are required. These alloys find

(Text continued on page 203.)

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TABLE 4.31 Typical Heat Treatments for Aluminum Alloy Mill Products[a]

Alloy	Product	Solution heat treatment[b]		Precipitation heat treatment		
		Metal temperature[c] °C	Temper designation	Metal temperature[c] °C	Approx. time of temperature,[d] h	Temper designation
2036	Sheet	[e]	T4			
2038	Sheet	[e]	T4			
6009	Sheet	[e]	T4	200–210	1	T6[f]
6010	Sheet	[e]	T4	200–210	1	T6[f]
6061	Sheet	515–550	T4	155–165	18	T6
	Plate	515–550	T451	155–165	18	T651
	Extrusions, tube, rod, bar forgings	515–550[g]	T4	170–180	8	T6
6063	Extrusions, tube	[g]	T1	175–185[h]	3	T5
		515–525[g]	T4	170–180[i]	8	T6
6111	Sheet	[e]	T4	200–210	1	T6
6463	Extrusions	[g]	T1	175–185[h]	3	T5
		515–525[g]	T4	170–180[i]	8	T6
7021	Sheet	395–405[j]	W	[l]	[l]	T61
7029	Extrusions	480–520[k]	W	[m]	[m]	T5, T6
7116	Extrusions	425–540	W	[n]	[n]	T5
7129	Extrusions	480–520	S	[m]	[m]	T5, T6

[a] The times and temperatures shown are typical for various forms, sizes, and methods of manufacture and may not exactly describe the optimum treatment for a specific item.

[b] Material should be quenched in water or by high-velocity fans from the solution heat-treating temperature as rapidly as possible and with minimum delay after removal from the furnace. Unless otherwise indicated, when material is quenched by total immersion in water, the water should be at room temperature and suitably cooled to remain below 35°C during the quench cycle. The use of high-velocity, high-volume jets of cold water is also effective for some material.

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[c] The metal temperature should be attained as rapidly as possible. Where a temperature range exceeding 10°C is shown, a temperature range of 10° within the listed range should be selected and maintained during the time at temperature.

[d] The time at temperature will depend on the time required for load to reach temperature. The times shown are based on rapid heating with soaking time measured from the time the load reaches the 10°C range listed or selected.

[e] These alloys are supplied in the solution heat-treated condition. For optimum properties, subsequent reheat treatment is not recommended.

[f] Mechanical properties of material will meet tensile property limits of T6 temper.

[g] By suitable control of extrusion temperature, product may be quenched directly from extrusion press to provide specified properties for this temper. Some products may be adequately quenched in air blast at room temperature.

[h] An alternate treatment comprised of 1–2 h at 200–210°C may be used.

[i] An alternate treatment comprised of 6 h at 175–185°C may be used.

[j] Quenched at a minimum average cooling rate of 35°C/s as measured over the range 385–205°C.

[k] 10-min soak at temperature followed by cold water quench.

[l] A minimum of 8 h at room temperature followed by 2 h at 95–105°C plus 4 h at 155–165°C.

[m] 5 h at 95–105°C plus 5 h at 155–165°C.

[n] 5 h at 95–105°C plus 5 h at 160–170°C.

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TABLE 4.32 Typical Mechanical Properties and Comparative Characteristics of Aluminum Alloys

	Typical mechanical properties[a,c]								Comparative characteristics					
	Tension			Shear	Fatigue	Modulus	Resistance to corrosion					Weldability[q]		
	Strength		Elongation											
Alloy and temper[b]	Ultimate, MPa	Yield 0.2% offset, MPa	Percent in 50 mm (1.60 mm thick specimen)	Ultimate shearing strength, MPa	Endurance limit, MPa	Modulus[g] of elasticity, MPa × 10³	General[h]	Stress-corrosion cracking[i]	Toughness[n]	Workability (cold)[p]	Machinability[p]	Gas	Arc	Resistance spot and seam
1100-0	90	35	35	60	35[d]	69	A	A		A	E	A	A	B
2017-T4	425	275	20[k]	260	125[d]	75	D	C		C	B	N/A	N/A	N/A
2024-T4	470	325	20	285	140[d]	73	D	C		C	B	N/A	N/A	N/A
2036-T4	340	195	24	205	125[e]	71	C	A2[l]	A	B	C	—	B	B
2038-T4	325	170	25	205	125[e]	71	C	A2[l]		B	C	—	B	B
2117-T4	295	165	24[k]	195	95[d]	71	C	A		B	C	N/A	N/A	N/A
3002-0	95	40	33	70		69	A	A		A	E	A	A	B
3003-H14, H24	150	145	8	95	60[d]	69	A	A		B	D	A	A	A
3004-0	180	70	20	110	95[d]	69	A	A	B	A	D	B	A	B
-H32	215	170	10	115	105[d]	69	A	A		B	D	B	A	A
5005-0	125	40	25	75		69	A	A		A	E	A	A	B
5052-0	195	90	25	125	110[d]	70	A	A	A	A	D	A	A	B
-H32	230	195	12	140	115[d]	70	A	A		B	D	A	A	A
-H34	260	215	10	145	125[d]	70	A	A	B	B	C	A	A	A
5083-H321, H116	315	230	14[k]		160[d]	71	A	B		C	D	C	A	A
5086-H32	290	205	12			71	A	A		B	D	C	A	A
-H34	325	255	10		185[d]	71	A	B		B	C	C	A	A
-H112	270	130	14			71	A	A		A	D	C	A	B
5182-0	275	130	21	165	140[e]	71	A-B	A2[m]		A	D	C	A	B
-02	270	125	23			71	A–B	A2[m]		A	D	C	A	B
5252-H25	235	170	11	145		69	A	A		B	C	A	A	A
5454-0	250	115	22	160		70	A	A	A	A	D	C	A	B
-H32	275	205	10	165		70	A	A		B	D	C	A	A
-H34	305	240	10	180		70	A	A	B	B	C	C	A	A
5457-H25	180	160	12	110		69	A	A		A	E	A	A	B
5657-H25	160	140	12	95		69	A	A		B	D	A	A	A
6009-T4	220	125	25	150	115[e]	69	B	A2	A	A	C	A	A	A
6010-T4	290	165	24	195	125[e]	69	B	A2	A	B	C	A	A	A

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6053-T61						69	A	A	—	—	C	N/A	N/A	N/A
6061-T4	240	145	22	165	95[d]	69	B	B	A	B	C	A	A	A
-T6, T651	310	275	12	205	95[d]	69	B	A	B	C	C	A	A	A
6063-T1	150	90	20	95	60[d]	69	A	A		B	D	A	A	A
-T5	185	145	12	115	70[d]	69	A	A		B	C	A	A	A
-T6	240	215	12	150	70[d]	69	A	A		C	C	A	A	A
6111-T1	290	160	26		69	69	B	A2	A	B	C	A	A	B
6463-T521	185	145	12			69	A	A		B	C	A	A	A
7021-T61	430	380	13		140[d]	71	B	A2[j]						
7029-T5, T6	430	380	15	270		70	B	A2[j]						
7116-T5	360	315	16				B	A1[j]		C				
7129-T6	430	380	15	270	145[f]	70	B	A2[j]						

[a] Typical properties are not guaranteed since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

[b] Only the commonly used tempers are listed for the alloys shown. Other tempers of these alloys are available.

[c] The indicated typical mechanical properties for all except the O temper material are higher than the specified minimum properties. For O temper products, typical ultimate and yield values are slightly lower than specified (maximum) values.

[d] Based on 500,000,000 cycles of completely reversed stress using the RR Moore type of machine and specimen.

[e] Based on a single series of tests, 10,000,000 cycles sheet flexural specimens.

[f] Based on 50,000,000 cycles in a single series of tests using the RR Moore type of machine and specimen.

[g] Average of tension and compression moduli. Compression modulus is about 2% greater than tension modulus.

[h] General corrosion ratings are based on exposures to sodium chloride solution by intermittent spraying or immersion. Ratings A through D are relative ratings in decreasing order of merit. The ratings do not necessarily imply acceptable performance in the intended application.

[i] Stress-corrosion cracking ratings are based on *service experience* and on *laboratory tests* of specimens exposed to the 35% sodium chloride alternate immersion test for 2XXX, 6XXX, and copper containing 1XXX series alloys and total immersion in boiling in sodium chloride solution for 96 h for copper free 7XXX series alloys.

A No known instance of failure in service or in laboratory tests.

A2 Insufficient service experience; no known instance of failure in laboratory tests.

B No known instance of failure in service; limited failures in laboratory tests of short transverse specimens.

B2 Insufficient service experience; limited failures in laboratory service.

C Service failures with sustained tension stress acting in short transverse direction relative to grain structure; limited failures in laboratory tests of long transverse specimens.

D Limited service failures with sustained longitudinal or long transverse stress.

[j] Improved resistance to stress corrosion cracking can be realized by using controlled quenching and artificial aging practices in heat-treatable 7XXX aluminum alloys.

[k] Elongation in 50 mm apply for thicknesses up through 12.50 mm and in $5D$ $(5.65\sqrt{A})$ for thicknesses over 12.50 mm, where D and A are the diameter and cross-sectional area of the specimen. Values for elongations in $5D$ $(5.65\sqrt{A})$ are shown in brackets.

[l] This rating would be B2 for material exposed to elevated temperatures.

[m] This rating may be different for material held at elevated temperatures for long periods.

[n] Toughness ratings are based upon Kahn tear test of 1.60-mm-thick sheet specimens in both longitudinal and transverse directions. These data are based on a limited number of tests and should be used for general comparisons only.

Ratings: A over 175 000 N·m/m²
B over 140 000 thru 175 000 N·m/m²
C over 105 000 thru 140 000 N·m/m²
D 0 through 105 000 N·m/m²

[p] Ratings A through D for workability (cold) and A through E for machinability are relative ratings in decreasing order of merit.

[q] Ratings A through D for weldability are relative ratings as follows:

A Generally weldable by all commercial procedures and methods.

B Weldable with special techniques.

C Limited weldability due to crack sensitivity, loss in corrosion resistances, loss in mechanical properties.

D No commonly used welding methods have been developed.

N/A Rating not applicable for end use application requirements, that is, rivets.

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TABLE 4.33 Typical Physical Properties of SAE Casting Alloys

Alloy			Density		Approximate melting range[§]		Elec. cond.,	Therm. cond.,	Coeff. of thermal expan., $\times 10^{-6}$			
UNS	ANSI	Temper	lb/in^3	kg/m^3	°F	°C	% IACS	W/(m · K)	68–212°F per °F	20–100°C per °C	68–572°F per °F	20–300°C per °C
A02010	201.0	T6	0.101	2800	995–1200	535–650	30	121	10.7	19.3	13.7	24.7
		T7	0.101	2800	995–1200	535–650	30	121	10.7	19.3	13.7	24.7
A02060	206.0	T4	0.101	2800	1010–1200	542–650	—	121	10.7	19.3	—	—
A02080	208.0	F	0.101	2800	970–1160	521–627	31	125	12.4	22.3	13.4	24.1
		T4	0.101	2800	970–1160	521–627	—	—	12.4	22.3	13.4	24.1
		T55	0.101	2800	970–1160	521–627	—	—	12.4	22.3	13.4	24.1
		T6	0.101	2800	970–1160	521–627	—	—	12.4	22.3	13.4	24.1
		T7	0.101	2800	970–1160	521–627	—	—	12.4	22.3	13.4	24.1
A02220	222.0	0	0.107	2960	965–1155	518–624	—	—	12.3	22.1	13.1	23.6
		T551	0.107	2960	965–1155	518–624	—	—	12.3	22.1	13.1	23.6
		T61	0.107	2960	965–1155	518–624	33	130	12.3	22.1	13.1	23.6
		T65	0.107	2960	965–1155	518–624	—	—	12.3	22.1	13.1	23.6
A02420	242.0	0	0.102	2820	990–1175	532–635	—	—	12.6	22.7	13.6	24.5
		T571*	0.102	2820	990–1175	532–635	34	134	12.6	22.7	13.6	24.5
		T61	0.102	2820	990–1175	532–635	—	—	12.6	22.7	13.6	24.5
		T77	0.102	2820	990–1175	532–635	38	151	12.6	22.7	13.6	24.5
A02950	295.0	T4	0.102	2820	970–1190	521–643	—	138	12.7	22.9	13.8	24.8
		T6	0.102	2820	970–1190	521–643	35	138	12.7	22.9	13.8	24.8
		T62	0.102	2820	970–1190	521–643	—	138	12.7	22.9	13.8	24.8
		T7	0.102	2820	970–1190	521–643	—	—	12.7	22.9	13.8	24.8
A02960	296.0	T4	0.101	2800	970–1170	521–632	—	130	12.2	22.0	13.3	23.9
		T6*	0.101	2800	970–1170	521–632	33	130	12.2	22.0	13.3	23.9
		T7	0.101	2800	970–1170	521–632	—	—	12.2	22.0	13.3	23.9
A03190	319.0	F	0.101	2800	960–1120	516–604	27	109	11.9	21.4	12.7	22.9
		T5	0.101	2800	960–1120	516–604	—	—	11.9	21.4	12.7	22.9
		T6	0.101	2800	960–1120	516–604	—	—	11.9	21.4	12.7	22.9
		T61	0.101	2800	960–1120	516–604	—	—	11.9	21.4	12.7	22.9
A23190	B319.0	T5	—	—	—	—	—	—	—	—	—	—
		T6	—	—	—	—	—	—	—	—	—	—

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A03280	328.0	F	0.098	2720	1025–1105	552–596	30	121	11.9	21.4	12.9	23.2
		T6	0.098	2720	1025–1105	552–596	—	—	11.9	21.4	12.9	23.2
A03320	332.0	T5*	0.100	2770	970–1080	521–582	26	104	11.5	20.7	12.4	22.3
A03330	333.0	F*	0.100	2770	960–1085	516–585	26	104	11.4	20.5	12.4	22.3
		T5*	0.100	2770	960–1085	516–585	29	117	11.4	20.5	12.4	22.3
		T6*	0.100	2770	960–1085	516–585	29	117	11.4	20.5	12.4	22.3
		T7*	0.100	2770	960–1085	516–585	35	138	11.4	20.5	12.4	22.3
A03360	336.0	T551*	0.098	2720	1000–1050	538–566	29	117	11.0	19.8	12.0	21.6
		T65	0.098	2720	1000–1050	538–566	—	—	11.0	19.8	12.0	21.6
A03390	339.0	T551*	0.098	2720	—	—	—	117	—	—	—	—
A03540	354.0	T61	0.098	2720	1000–1105	538–596	32	125	11.6	20.9	12.7	22.9
A03550	355.0	T51	0.098	2720	1015–1150	546–621	43	167	12.4	22.3	13.7	24.7
		T6	0.098	2720	1015–1150	546–621	36	142	12.4	22.3	13.7	24.7
		T62*	0.098	2720	1015–1150	546–621	36	142	12.4	22.3	13.7	24.7
		T7	0.098	2720	1015–1150	546–621	42	163	12.4	22.3	13.7	24.7
		T71	0.098	2720	1015–1150	546–621	39	151	12.4	22.3	13.7	24.7
A33550	C355.0	T6	0.098	2720	1015–1150	546–621	36	142	12.4	22.3	13.7	24.7
		T61	0.098	2720	1015–1150	546–621	37	146	12.4	22.3	13.7	24.7
A03560	356.0	F	0.097	2685	1035–1135	557–613	—	—	11.9	21.4	12.9	23.2
		T51	0.097	2685	1035–1135	557–613	43	167	11.9	21.4	12.9	23.2
		T6	0.097	2685	1035–1135	557–613	39	151	11.9	21.4	12.9	23.2
		T7	0.097	2685	1035–1135	557–613	40	155	11.9	21.4	12.9	23.2
		T71	0.097	2685	1035–1135	557–613	—	—	11.9	21.4	12.9	23.2
A13560	A356.0	T6	0.097	2685	1035–1135	557–613	—	—	11.9	21.4	12.9	23.2
		T61	0.097	2685	1035–1135	557–613	39	151	11.9	21.4	12.9	23.2
		T7	0.097	2685	1035–1135	557–613	—	—	11.9	21.4	12.9	23.2
		T71	0.097	2685	1035–1135	557–613	—	—	11.9	21.4	12.9	23.2
A03570	357.0	T6	0.097	2685	1035–1135	557–613	39	151	11.9	21.4	12.9	23.2
A13570	A357.0	T61	0.097	2685	1035–1135	557–613	39	151	11.9	21.4	12.9	23.2
A03590	359.0	T61	0.097	2685	1045–1115	563–602	35	138	11.6	20.9	12.7	22.9
A03600	360.0	F	0.095	2630	1035–1105	557–596	—	—	12.2†	22.0†	—	—
A13600	A360.0	F	0.095	2630	1035–1105	557–596	29	113	12.2†	22.0†	—	—
A03800	380.0	F	0.098	2720	1000–1100	538–593	23	96	12.1†	21.8†	—	—
A13830	A380.0	F	0.098	2720	1000–1100	538–593	—	100	—	—	—	—
A03830	383.0	F	0.098	2720	960–1080	516–582	23	96	11.7†	21.1†	—	—
A03840	384.0	F	0.098	2720	960–1080	516–582	23	96	11.7†	21.1†	—	—

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TABLE 4.33 Typical Physical Properties of SAE Casting Alloys (*Continued*)

Alloy			Density		Approximate melting range[§]		Elec. cond.,	Therm. cond.,	Coeff. of thermal expan., $\times 10^{-6}$			
UNS	ANSI	Temper	lb/in^3	kg/m^3	°F	°C	% IACS	W/(m · K)	68–212°F per °F	20–100°C per °C	68–572°F per °F	20–300°C per °C
A03900	390.0	F	—	—	—	—	—	—	—	—	—	—
A13900	A390.0	T5	0.099	2740	945–1200	507–649	25	134	10.0	18.0	—	—
		T6	0.099	2740	945–1200	507–649	—	—	10.0	18.0	—	—
		T7	0.099	2740	945–1200	507–649	—	—	10.0	18.0	—	—
A23900	B390.0	F	—	—	—	—	—	—	—	—	—	—
A04130	413.0	F	0.096	2660	1065–1080	574–582	—	—	11.9[†]	21.4[†]	—	—
A14130	A413.0	F	0.096	2660	1065–1080	574–582	31	121	11.9[†]	21.4[†]	—	—
A24430	B443.0	F	0.097	2685	1065–1170	574–632	37	146	12.3	22.1	13.4	24.1
A34430	C443.0	F	0.097	2685	1065–1170	574–632	37	142	12.9[†]	23.2[†]	—	—
A14440	A444.0	F	0.095	2635	1065–1145	574–618	41	159	12.1	21.8	13.2	23.8
A05140	514.0	F	0.096	2660	1085–1185	585–640	35	138	13.4	24.1	14.5	26.1
A05200	520.0	T4	0.093	2570	840–1120	449–604	21	88	13.7	24.7	14.8	26.6
A05350	535.0	F	0.095	2635	1020–1165	548–629	23	96	13.1	23.6	14.8	26.6
A07050	705.0	T5	0.100	2770	1105–1180	596–638	25	104	13.1	23.6	14.3	25.7
A07070	707.0	T5	0.100	2770	1085–1165	585–629	25	104	13.2	23.8	14.4	25.9
		T7	0.100	2770	1085–1165	585–629	—	—	13.2	23.8	14.4	25.9
A07100	710.0	T5	0.102	2820	1105–1195	596–646	35	138	13.4	24.1	14.6	26.3
A07120	712.0	T5	0.101	2800	1135–1200	613–649	35	138	13.7	24.7	14.8[‡]	26.6[c]
A07130	713.0	T5	0.102	2810	1100–1180	593–638	30	121	13.4[‡]	24.1[‡]	14.6[‡]	26.3[c]

[*] Chill cast samples; all other samples cast in green sand molds.
[†] For die cast alloys, data valid for temperature range of 68–392°F (20–200°C).
[‡] Estimated value.
[§] The approximate melting range data shown are a practical parameter of the alloy—not concise values. Normal and common composition and process variations can cause deviations from the values given.
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TABLE 4.34 Mechanical Property Limits of SAE Sand Casting Alloys*

Alloy		Temper	Min. tensile strength		Min. yield strength (0.2% offset)		Elongation % Min. in 4D	Brinell hardness† (500 kg)
UNS	ANSI		ksi	MPa	ksi	MPa		
A02010	201.0	T6	60.0	415	50.0	345	5.0	115–145
		T7	60.0	415	50.0	345	3.0	115–145
A02060	206.0	T4	40.0	275	24.0	165	8.0	—
A02080	208.0	F	19.0	130	12.0	85	1.5	40–70
		T55	21.0	145	—	—	—	—
A02220	222.0	0	23.0	160	—	—	—	—
		T61	30.0	205	—	—	—	100–130
A02420	242.0	0	23.0	160	—	—	—	—
		T571	29.0	200	—	—	—	—
		T61	32.0	220	20.0	140	—	90–120
		T77	24.0	165	13.0	90	1.0	—
A02950	295.0	T4	29.0	200	13.0	90	6.0	45–75
		T6	32.0	220	20.0	140	3.0	60–90
		T62	36.0	250	28.0	195	—	80–110
		T7	29.0	200	16.0	110	3.0	55–85
A03190	319.0	F	23.0	160	13.0	90	1.5	55–85
		T5	25.0	170	—	—	—	—
		T6	31.0	215	20.0	140	1.5	65–95
A23190	B319.0	T5	26.0‡	180‡	—	—	—	—
		T6	32.0‡	220‡	21.0‡	145‡	1.0‡	70–100‡
A03280	328.0	F	25.0	170	14.0	95	1.0	45–75
		T6	34.0	235	21.0	145	1.0	65–95

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TABLE 4.34 Mechanical Property Limits of SAE Sand Casting Alloys* (*Continued*)

Alloy			Min. tensile strength		Min. yield strength (0.2% offset)		Elongation % Min. in 4D	Brinell hardness† (500 kg)
UNS	ANSI	Temper	ksi	MPa	ksi	MPa		
A03550	355.0	T51	25.0	170	18.0	125	—	50–80
		T6	32.0	220	20.0	140	2.0	65–95
		T7	35.0	240	—	—	—	—
		T71	30.0	205	22.0	150	—	60–90
A33550	C355.0	T6	36.0	250	25.0	170	2.5	—
		T61	36.0‡	250‡	30.0‡	205‡	1.0‡	70–100‡
A03560	356.0	F	19.0	130	—	—	2.0	40–70
		T51	23.0	160	16.0	110	—	45–75
		T6	30.0	205	20.0	140	3.0	55–85
		T7	31.0	215	29.0	200	—	60–90
		T71	25.0	170	18.0	125	3.0	45–75
A13560	A356.0	T6	34.0	235	24.0	165	3.5	55–85
		T7	32.0‡	220‡	30.0‡	205‡	—	—
		T71	26.0‡	180‡	19.0‡	130‡	4.0‡	—
A03570	357.0	T6§	—	—	—	—	—	—
A13570	A357.0	T61§	—	—	—	—	—	—
A03590	359.0	T61§	—	—	—	—	—	—
A13900	A390.0	F	26.0‡	180‡	26.0‡	180‡	—	85–115‡
		T5	26.0‡	180‡	26.0‡	180‡	—	85–115‡
		T6	40.0‡	275‡	40.0‡	275‡	—	125–155‡
		T7	36.0‡	250‡	36.0‡	250‡	—	100–130‡
B24430	B443.0	F	17.0	115	6.0	40	3.0	25–55
A14440	A444.0	F	18.0‡	125‡	7.0‡	50‡	8.0‡	35–65‡
A05140	514.0	F	22.0	150	9.0	60	6.0	35–65

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A05200	520.0	T4	42.0	290	22.0	150	12.0	60–90
A05350	535.0	F	35.0	240	18.0	125	9.0	60–90
A07050	705.0	T5	30.0	205	17.0	115	5.0	50–80
A07070	707.0	T5	33.0	230	22.0	150	2.0	60–90
		T7	37.0	255	30.0	205	1.0	65–95
A07100	710.0	T5	32.0	220	20.0	140	2.0	60–90
A07120	712.0	T5	34.0	235	25.0	170	4.0	60–90
A07130	713.0	T5	32.0	220	22.0	150	3.0	60–90

* Values represent properties obtained from 0.500 in diameter separately cast test bars as depicted in Fig. 8 of ASTM B 557, cast in green sand molds, and tested in accordance with the procedures of ASTM B 557.

† Hardness values are given for information only; not required for acceptance.

‡ Preliminary value.

§ Mechanical properties for these alloys are dependent on casting process and heat treat procedures set for individual casting requirements. These alloys have generally been used in premium quality applications, and process techniques have not been standardized. Consult individual foundry for applicable property limits.

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TABLE 4.35 Typical Uses of SAE Aluminum Casting Alloys and Similar Specifications

Alloy designations			Type of casting*	Similar specifications			Typical uses and general data
UNS	ANSI	Former SAE		ASTM	Federal	AMS	
A02010	201.0	382	S	B26	—	—	Very high strength at room and elevated temperature; good impact strength and ductility; high-cost premium casting alloy.
			PM	—	—	4229	
A02060	206.0	—	S	—	—	4237	High tensile and yield strength with moderate ductility; good fracture toughness in T4 temper, structural parts for automotive and aerospace applications.
			PM	—	—	—	
A02080	208.0	380	S	B26	QQ-A-601	—	Manifolds, valve bodies, and similar castings requiring pressure tightness.
			PM	B108	—	—	
A02220	222.0	34	S	B26	QQ-A-601	—	Primarily a piston alloy, but also used for aircooled cylinder heads and valve tappet guides.
			PM	B108	QQ-A-596	—	
A02420	242.0	39	S	B26	QQ-A-601	4222	Used primarily for aircooled cylinder heads, but also for pistons in high-performance gasoline engines.
			PM	B108	QQ-A-596	—	
A02950	295.0	38	S	B26	QQ-A-601	4231	General structural castings requiring high strength and shock resistance.
A02960	296.0	—	PM	B108	QQ-A-596	4282	Modification of alloy 295.0 for use in permanent molds.
A03190	319.0	326	S	B26	QQ-A-601	—	General-purpose low-cost alloy; good foundry characteristics.
			PM	B108	QQ-A-596	—	
A23190	B319.0	329	S	—	—	—	General-purpose alloy similar to 319.0, but with lower ductility and improved machinability.
			PM	—	—	—	
A03280	328.0	327	S	B26	QQ-A-601	—	Similar to alloys 355.0 and 356.0, but lower ductility.
A03320	332.0	332	PM	B108	QQ-A-596	—	Primarily used for automotive and compressor pistons.

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A03330	333.0	331	PM	B108	QQ-A-596	—	General-purpose low-cost permanent mold alloy used for engine parts, motor housings, flywheel housings, and regulator parts.
A03360	336.0	321	PM	B108	QQ-A-596	—	Piston alloy having low expansion.
A03390	339.0	334	PM	—	—	—	Piston alloy.
A03540	354.0	—	PM	B108	—	—	High-strength premium quality casting alloy.
				B686	—	—	
A03550	355.0	322	S	B26	QQ-A-601	4210	General use where high strength, medium ductility, and pressure tightness are required, such as pump bodies and liquid-cooled cylinder heads.
			PM	B108	QQ-A-596	4212	
				—	—	4214	
				—	—	4280	
				—	—	4281	
A33550	C355.0	335	S	B26	QQ-A-601	4215	Similar to alloy 355.0, but has greater ductility.
			PM	B108	QQ-A-596	—	
				B686	—	—	
A03560	356.0	323	S	B26	QQ-A-601	4217	For intricate castings requiring good strength and ductility.
			PM	B108	QQ-A-596	4284	
				—	—	4286	
A13560	A356.0	336	S	B26	QQ-A-601	4218	Similar to alloy 356.0, but has greater ductility.
			PM	B108	QQ-A-596	—	
				B686	—	—	
A03570	357.0	—	S	—	—	—	Similar to alloy A357.0, but has greater ductility.
			PM	B108	QQ-A-596	—	
A13570	A357.0	—	S	—	—	4219	High-strength structural alloy with good ductility.
			PM	B108	—	—	
				B686	—	—	
A03590	359.0	—	S	—	—	—	High-strength structural alloy with good ductility.
			PM	B108	—	—	
A03600	360.0	—	D	B85	—	—	Very good casting characteristics; good corrosion resistance; used in place of alloy 413 where higher mechanical properties are required.

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TABLE 4.35 Typical Uses of SAE Aluminum Casting Alloys and Similar Specifications (*Continued*)

Alloy designations			Type of casting*	Similar specifications			Typical uses and general data
UNS	ANSI	Former SAE		ASTM	Federal	AMS	
A13600	A360.0	309	D	B85	QQ-A-591	4290	Excellent casting characteristics; suited for use in thin-walled or intricate castings produced in cold-chamber casting machine; high corrosion resistance; slightly higher mechanical properties than alloy 360.0.
A03800	380.0	308	D	B85	QQ-A-591	—	Similar to alloy A380.0, but suitable for use in either cold-chamber or gooseneck machines.
A13800	A380.0	306	D	B85	QQ-A-591	4291	Good casting characteristics and fair resistance to corrosion; not especially suited for thin sections; limited to cold-chamber machines.
A03830	383.0	383	D	B85	QQ-A-591	—	Similar to alloy 380.0, but with improved castability.
A03840	384.0	303	D	B85	QQ-A-591	—	General-purpose alloy with high fluidity; used for thin-walled castings or castings with large areas.
A03900	390.0	—	D	—	—	—	High wear resistance; used for cylinder blocks, transmission pump and air compressor housings, small engine crankcases, and air conditioner pistons.
A13900	A390.0	—	S	—	—	—	Similar to 390.0, but formulated for sand and permanent mold casting.
			PM	—	—	—	
A23900	B390.0	—	D	—	—	—	Similar to alloy 390.0.
A04130	413.0	—	D	B85	—	—	Good for large thin-wall die castings, difficult to machine and finish.
A14130	A413.0	305	D	B85	QQ-A-591	—	High corrosion resistance; excellent castability; used for complicated castings with thin sections, also difficult to machine and finish.
A24430	B443.0	35	S	B26	QQ-A-601	—	Used for intricate castings having thin sections; good corrosion resistance; fair strength and good ductility.
			PM	B108	QQ-A-596	—	

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A34430	C443.0	304	D	B85	QQ-A-591	—	Good casting characteristics and resistance to corrosion.
A14440	A444.0	—	S	—	—	—	Good castability; excellent ductility for impact absorption; used for bridge railing posts and turbocharger compressor housings.
A05140	514.0	320	S	B26	QQ-A-601	—	Moderate strength; very high corrosion resistance.
A05200	520.0	324	S	B26	QQ-A-601	4240	High-strength structural alloy; requires special foundry and heat treat practice; susceptible to stress corrosion failure.
A05350	535.0	—	S	B26	QQ-A-601	—	Excellent shock and corrosion resistance, dimensional stability, and machinability; used in computer components, frame sections, optical equipment, and applications where stress rupture is a factor.
A07050	705.0	311	S	B26	QQ-A-601	—	High-strength general-purpose alloy; excellent machinability and dimensional stability; high corrosion resistance; can be anodized.
			PM	B108	QQ-A-596	—	
A07070	707.0	312	S	B26	QQ-A-601	—	Similar to alloy 705.0, but higher strength and lower ductility.
			PM	B108	QQ-A-596	—	
A07100	710.0	313	S	B26	QQ-A-601	—	High-strength general-purpose alloy similar to alloys 705.0 and 707.0; easily polished.
A07120	712.0	310	S	B26	QQ-A-601	—	General-purpose structural castings developing strengths equivalent to alloy 295.0 without requiring heat treatment, but casting characteristics slightly poorer than alloy 295.0.
A07130	713.0	315	S	B26	QQ-A-601	—	Similar to alloy 710.0.
			PM	B108	QQ-A-596	—	

* S—sand cast; PM—permanent mold; D—die cast.

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TABLE 4.36 SAE Aluminum Alloy Characteristics

Alloy designations			Foundry characteristics[a]						
				Pattern shrinkage allowance[b]					
UNS	ANSI	Former SAE	Type of casting	in/ft	%	Resistance to hot cracking[c]	Pressure tightness	Fluidity[d]	Solidification shrinkage tendency[e]
A02010	201.0	382	S	5/32	1.30	4	3	3	4
			PM	[b]	[b]	4	3	3	4
A02060	206.0	—	S	5/32	1.30	4	3	3	4
			PM	[b]	[b]	4	3	3	4
A02080	208.0	380	S	5/32	1.30	4	3	3	3
			PM	[b]	[b]	4	3	3	3
A02220	222.0	34	S	5/32	1.30	3	3	3	3
			PM	[b]	[b]	4	4	3	4
A02420	242.0	39	S	5/32	1.30	4	3	3	4
			PM	[b]	[b]	4	4	3	4
A02950	295.0	38	S	5/32	1.30	4	4	3	3
A02960	296.0	—	PM	[b]	[b]	4	3	3	3
A03190	319.0	326	S	5/32	1.30	2	2	2	2
			PM	[b]	[b]	2	2	2	3
A23190	B319.0	329	S	5/32	1.30	2	2	2	2
			PM	[b]	[b]	2	2	2	2
A03280	328.0	327	S	5/32	1.30	1	1	1	1
A03320	332.0	332	PM	[b]	[b]	1	2	1	2
A03330	333.0	331	PM	[b]	[b]	2	2	1	3
A03360	336.0	321	PM	[b]	[b]	1	2	1	3
A03390	339.0	334	PM	[b]	[b]	1	2	1	2
A03540	354.0	—	PM	[b]	[b]	2	1	1	3
A03550	355.0	322	S	5/32	1.30	1	1	1	1
			PM	[b]	[b]	1	1	2	2
A33550	C355.0	335	S	5/32	1.30	1	1	1	1
			PM	[b]	[b]	1	1	2	2
A03560	356.0	323	S	5/32	1.30	1	1	1	1
			PM	[b]	[b]	1	1	2	1

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TABLE 4.36 SAE Aluminum Alloy Characteristics (*Continued*)

Alloy		Other characteristics										
UNS	ANSI	Normally heat treated	Resistance to corrosion[f]	Machining[g]	Polishing[h]	Electro-plating[i]	Anodized appearance[j]	Chemical oxide coating[k] (protection)	Strength at elevated temperature[l]	Suitability for welding[m]	Suitability for brazing[n]
A02010	201.0	Yes	4	1	1	1	2	2	1	4	No
A02060	206.0	Yes	4	1	1	1	2	2	1	4	No
A02080	208.0	Yes	4	3	2	1	3	2	2	4	No
A02220	222.0	Yes	4	1	2	1	3	4	1	4	No
A02420	242.0	Yes	4	2	2	1	3	4	1	4	No
A02950	295.0	Yes	3	2	2	1	2	3	3	3	No
A02960	296.0	Yes	4	3	4	2	4	3	3	2	No
A03190	319.0	Yes	3	3	4	2	4	3	3	2	No
A23190	B319.0	Yes	3	3	4	2	4	3	3	2	No
A03280	328.0	Yes	3	4	5	2	4	2	2	2	No
A03320	332.0	Aged only	3	3	4	3	5	3	3	2	No
A03330	333.0	Yes	3	2	3	2	4	3	2	3	No
A03360	336.0	Yes	3	4	5	4	5	2	2	2	No
A03390	339.0	Aged only	3	3	4	3	5	3	3	2	No
A03540	354.0	Yes	3	4	4	2	4	3	2	3	No
A03550	355.0	Yes	3	3	3	1	4	2	2	2	No
A33550	C355.0	Yes	3	3	3	2	4	2	2	2	No
A03560	356.0	Yes	2	4	3	2	4	2	3	1	No
A13560	A356.0	Yes	2	3	3	1	4	2	3	1	No
A03570	357.0	Yes	2	3	3	1	4	2	3	1	No
A13570	A357.0	Yes	2	3	3	1	4	2	3	1	No
A03590	359.0	Yes	2	4	4	2	4	2	2	1	No
A03600	360.0	No	2	4	4	2	4	3	2	3	No
A13600	A360.0	No	3	3	3	1	4	3	2	3	No
A03800	380.0	No	4	3	3	1	4	5	2	4	No
A13800	A380.0	No	4	3	3	1	4	5	2	4	No
A03830	383.0	No	4	3	3	1	4	5	2	4	No
A03840	384.0	No	4	3	3	1	4	5	3	4	No

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A03900	390.0	No	3	4	3	—	5	—	1	4	No
A13900	A390.0	Yes	3	4	3	—	5	—	1	4	No
A23900	B390.0	No	3	4	3	—	5	—	1	4	No
A04130	413.0	No	2	4	5	3	5	3	3	3	No
A14130	A413.0	No	3	4	5	3	5	3	3	3	No
A24430	B443.0	No	3	5	5	2	5	2	4	1	Ltd.
A34430	C443.0	No	2	5	5	2	4	3	5	1	No
A14440	A444.0	No	2	4	4	—	4	2	3	1	No
A05140	514.0	No	1	1	1	5	1	1	2	4	No
A05200	520.0	Yes	1	1	1	4	1	1	[p]	5	No
A05350	535.0	Opt	1	1	1	—	1	1	3	4	No
A07050	705.0	Aged only	2	1	1	3	2	2	5	4	Yes
A07070	707.0	Yes	2	1	1	3	2	2	5	4	Yes
A07100	710.0	Aged only	2	1	1	2	2	3	5	4	Yes
A07120	712.0	Aged only	2	1	1	2	2	3	5	4	Yes
A07130	713.0	Aged only	2	1	1	2	2	3	5	4	Yes

NOTE: Type of casting: S—sand cast; PM—permanent mold; D—die cast.

[a] 1 indicates best of group; 5 indicates poorest of group.

[b] Not applicable to permanent mold and die castings. Allowances are for average sand castings. Shrinkage requirements will vary with intricacy of design and dimensions.

[c] Ability of alloy to withstand contraction stresses while cooling through hot-short or brittle temperature range.

[d] Ability of liquid alloy to flow readily in mold and fill thin sections.

[e] Decrease in volume accompanying freezing of alloy and measure of amount of compensating feed metal required in form of risers.

[f] Based on alloy resistance in 5% salt spray test (ASTM B117).

[g] Composite rating based on ease of cutting, chip characteristics, quality of finishing, and tool life. Ratings, in the case of heat treatable alloys, based on T6 temper. Other tempers, particularly the annealed temper, may have lower rating.

[h] Composite rating based on ease and speed of polishing and quality of finish provided by typical polishing procedure.

[i] Ability of casting to take and hold on electroplate applied by present standard methods.

[j] Rated on lightness of color, brightness, and uniformity of clear anodized coating applied in sulfuric acid electrolyte.

[k] Rated on combined resistance of coating and base alloy to corrosion.

[l] Rating based on tensile and yield strengths of temperature up to 500°F (260°C), after prolonged heating at testing temperatures.

[m] Based on ability of material to be fusion welded with filler rod of same alloy.

[n] Refers to suitability of alloy to withstand brazing temperatures without excessive distortion or melting.

[p] Not recommended for service at temperatures exceeding 200°F (93°C).

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Materials: Physical Properties, Characteristics, and Uses

TABLE 4.37 Mechanical Properties of Aluminum: Typical Properties

Alloy and temper	Tension				Brinell hardness[a]	Ultimate shear strength, psi	Endurance limit, psi	Mod. of elast., psi
	Strength, psi		% Elong. in 2 in					
	Ultimate	Yield	1/16 in (thick)	1/2 in				
EC-O	12,000	4,000	—	—	—	8,000	—	10.0×10^6
EC-H14	16,000	14,000	—	—	—	10,000	—	10.0×10^6
EC-H19	27,000	24,000	—	—	—	15,000	7,000	10.0×10^6
1060-O	10,000	4,000	43	—	19	7,000	3,000	10.0×10^6
1060-H14	14,000	13,000	12	—	26	9,000	5,000	10.0×10^6
1100-O	13,000	5,000	35	45	23	9,000	5,000	10.0×10^6
1100-H12	16,000	15,000	12	25	28	10,000	6,000	10.0×10^6
1100-H14	18,000	17,000	9	20	32	11,000	7,000	10.0×10^6
1100-H16	21,000	20,000	6	17	38	12,000	9,000	10.0×10^6
1100-H18	24,000	22,000	5	15	44	13,000	9,000	10.0×10^6
2011-T3[b]	55,000	43,000	—	15	95	32,000	18,000	10.2×10^6
2011-T8	59,000	45,000	—	12	100	35,000	18,000	10.2×10^6
2014-O	27,000	14,000	—	18	45	18,000	13,000	10.6×10^6
2014-T4, T451	62,000	42,000	—	20	105	38,000	20,000	10.6×10^6
2014-T6, T651[c]	70,000	60,000	—	13	135	42,000	18,000	10.6×10^6
2017-T4, T451	62,000	40,000	—	22	105	38,000	18,000	10.5×10^6
2024-O	27,000	11,000	20	22	47	18,000	13,000	10.6×10^6
2024-T3	70,000	50,000	18	—	120	41,000	20,000	10.6×10^6
2024-T4, T351[c]	68,000	47,000	20	19	120	41,000	20,000	10.6×10^6
2024-T36	72,000	57,000	13	—	130	42,000	18,000	10.6×10^6
2024-T81, T851	70,000	65,000	6	—	128	43,000	18,000	10.6×10^6
2024-O[d]	26,000	11,000	20	—	—	18,000	—	10.6×10^6
2024-T3[d,e]	65,000	45,000	18	—	—	40,000	—	10.6×10^6
2024-T4, T351[d,e]	64,000	42,000	19	—	—	40,000	—	10.6×10^6
2024-T36[d,e]	67,000	53,000	11	—	—	41,000	—	10.6×10^6
2024-T81, T851[d,e]	65,000	60,000	6	—	—	40,000	—	10.6×10^6
2024-T86[d,e]	70,000	66,000	6	—	—	42,000	—	10.6×10^6
2219-O[f]	25,000	11,000	18	—	—	—	—	10.6×10^6
2219-T31, T351[f]	52,000	36,000	17	—	—	—	—	10.6×10^6
2219-T81, T851	66,000	51,000	10	—	—	—	15,000	10.6×10^6
3003-O	16,000	6,000	30	40	28	11,000	7,000	10.0×10^6
3003-H12	19,000	18,000	10	20	35	12,000	8,000	10.0×10^6
3003-H14	22,000	21,000	8	16	40	14,000	9,000	10.0×10^6
3003-H16	26,000	25,000	5	14	47	15,000	10,000	10.0×10^6
3003-H18	29,000	27,000	4	10	55	16,000	10,000	10.0×10^6
3004-O	26,000	10,000	20	25	45	16,000	14,000	10.0×10^6
3004-H32	31,000	25,000	10	17	52	17,000	15,000	10.0×10^6
3004-H34	35,000	29,000	9	12	63	18,000	15,000	10.0×10^6
3004-H36	38,000	33,000	5	9	70	20,000	16,000	10.0×10^6
3004-H38	41,000	36,000	5	6	77	21,000	16,000	10.0×10^6
3004-O[d]	26,000	10,000	20	25	—	16,000	—	10.0×10^6
3004-H32[d]	31,000	25,000	10	17	—	17,000	—	10.0×10^6
3004-H34[d]	35,000	29,000	9	12	—	18,000	—	10.0×10^6
3004-H36[d]	38,000	33,000	5	9	—	20,000	—	10.0×10^6
3004-H38[d]	41,000	36,000	5	6	—	21,000	—	10.0×10^6

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Materials: Physical Properties, Characteristics, and Uses

TABLE 4.37 Mechanical Properties of Aluminum: Typical Properties (*Continued*)

4032-T6	55,000	46,000	—	9	120	38,000	16,000	11.4×10^6
5005-O	18,000	6,000	25	—	28	11,000	—	10.0×10^6
5005-H14	23,000	22,000	6	—	—	19,000	—	10.0×10^6
5005-H32	20,000	17,000	11	—	36	14,000	—	10.0×10^6
5005-H34	23,000	20,000	8	—	41	14,000	—	10.0×10^6
5005-H36	26,000	24,000	6	—	46	15,000	—	10.0×10^6
5005-H38	29,000	27,000	5	—	51	16,000	—	10.0×10^6
5050-O	21,000	8,000	24	—	36	15,000	12,000	10.0×10^6
5050-H32	25,000	21,000	9	—	46	17,000	13,000	10.0×10^6
5050-H34	28,000	24,000	8	—	53	18,000	13,000	10.0×10^6
5050-H36	30,000	26,000	7	—	58	19,000	14,000	10.0×10^6
5050-H38	32,000	29,000	6	—	63	20,000	14,000	10.0×10^6
5052-O	28,000	13,000	25	30	47	18,000	16,000	10.2×10^6
5052-H32	33,000	28,000	12	18	60	20,000	17,000	10.2×10^6
5052-H34	38,000	31,000	10	14	68	21,000	18,000	10.2×10^6
5052-H36	40,000	35,000	8	10	73	23,000	19,000	10.2×10^6
5052-H38	42,000	37,000	7	8	77	24,000	20,000	10.2×10^6
5083-O	42,000	21,000	22	25	67	25,000	22,000	10.3×10^6
5083-H112	44,000	28,000	16	—	80	26,000	22,000	10.3×10^6
5083-H113	46,000	33,000	16	—	82	—	23,000	10.3×10^6
5083-H321	46,000	33,000	—	16	—	—	23,000	10.3×10^6
5083-H323	47,000	36,000	10	—	84	27,000	—	10.3×10^6
5086-O	38,000	17,000	22	30	60	23,000	21,000	10.3×10^6
5086-H32	42,000	30,000	12	16	72	25,000	22,000	10.3×10^6
5086-H34	47,000	37,000	10	14	82	27,000	23,000[h]	10.3×10^6
5086-H112	39,000	19,000	14	—	64	23,000	21,000[h]	10.3×10^6
5154-O	35,000	17,000	27	30	58	22,000	17,000	10.2×10^6
5154-H32	39,000	30,000	15	18	67	22,000	18,000	10.2×10^6
5154-H34	42,000	33,000	13	16	73	24,000	19,000	10.2×10^6
5154-H36	45,000	36,000	12	14	78	26,000	20,000	10.2×10^6
5154-H38	48,000	39,000	10	—	80	28,000	21,000	10.2×10^6
5154-H112	35,000	17,000	25	—	63	—	17,000	10.2×10^6
5454-O	36,000	17,000	22	25	62	23,000	—	10.2×10^6
5454-H32	40,000	30,000	10	18	73	24,000	—	10.2×10^6
5454-H34	44,000	35,000	10	16	81	26,000	—	10.2×10^6
5454-H112	36,000	18,000	18	—	62	23,000	—	10.2×10^6
5454-H311	38,000	26,000	14	—	70	23,000	—	10.2×10^6
5456-O	45,000	23,000	24	20	70	27,000	22,000	10.3×10^6
5456-H112	45,000	24,000	22	—	70	27,000	—	10.3×10^6
5456-H311	47,000	33,000	18	—	75	27,000	24,000	10.3×10^6
5456-H321	51,000	37,000	16	—	90	30,000	23,000	10.3×10^6
5456-H343	56,000	43,000	8	—	94	33,000	—	10.3×10^6
5457-O	19,000	7,000	22	—	32	12,000	—	10.0×10^6
5457-H32	22,000	19,000	9	—	40	14,000	—	10.0×10^6
5457-H34	25,000	22,000	8	—	45	15,000	—	10.0×10^6
5457-H36	28,000	26,000	7	—	51	17,000	—	10.0×10^6
5457-H38	30,000	27,000	6	—	55	18,000	—	10.0×10^6
6061-O	18,000	8,000	25	30	30	12,000	9,000	10.0×10^6
6061-T4, T451	35,000	21,000	22	25	65	24,000	14,000	10.0×10^6
6061-T6, T651	45,000	40,000	12	17	95	30,000	14,000	10.0×10^6

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Materials: Physical Properties, Characteristics, and Uses

TABLE 4.37 Mechanical Properties of Aluminum: Typical Properties (*Continued*)

Alloy and temper	Tension				Brinell hardness[a]	Ultimate shear strength, psi	Endurance limit, psi	Mod. of elast., psi
	Strength, psi		% Elong. in 2 in					
	Ultimate	Yield	1/16 in (thick)	1/2 in				
6061-O[d]	17,000	7,000	25	—	—	11,000	—	10.0×10^6
6061-T4, T451[d]	33,000	19,000	22	—	—	22,000	—	10.0×10^6
6061-T6, T651[d]	42,000	37,000	12	—	—	27,000	—	10.0×10^6
6063-O	13,000	7,000	—	—	25	10,000	8,000	10.0×10^6
6063-T4	25,000	13,000	22	—	—	16,000	—	10.0×10^6
6063-T5	27,000	21,000	12	22	60	17,000	10,000	10.0×10^6
6063-T6	35,000	31,000	12	18	73	22,000	10,000	10.0×10^6
6063-T832	42,000	39,000	12	—	95	27,000	—	10.0×10^6
6262-T9	58,000	55,000	—	10	120	35,000	13,000	10.0×10^6
7075-O	33,000	15,000	17	16	60	22,000	17,000	10.4×10^6
7075-T6, T651[g]	83,000	73,000	11	11	150	48,000	23,000	10.4×10^6
7075-O[d]	32,000	14,000	17	—	—	22,000	—	10.4×10^6
7075-T6, T651[d]	76,000	67,000	11	—	—	46,000	—	10.4×10^6
7079-T6, T651	78,000	68,000	—	14	145	45,000	23,000	10.4×10^6
7178-O	33,000	15,000	15	16	60	22,000	—	10.4×10^6
7178-T6, T651[e]	88,000	78,000	10	11	160	52,000	22,000	10.4×10^6

[a] 500-kg load; 10-mm ball.
[b] Sizes larger than 1½ in will have strengths slightly less than shown.
[c] Extruded shapes over ¾ in thick have strengths 15–20% higher than shown.
[d] These alloys are Alclad.
[e] Sheets thicker than 0.062 in will have strengths slightly higher than shown.
[f] Properties for sheets and plates only.
[g] Extruded products will have strengths approx. 10% higher.
[h] Applies to sheets and plates only.
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TABLE 4.38 Typical Characteristics and Applications of Wrought Aluminum

Alloy and temper	Resistance to corrosion		Work-ability (cold)[e]	Machin-ability[e]	Brazability[f]	Weldability[f]			Some applications of alloy
	General[a]	Stress-corrosion cracking[b]				Gas	Arc	Resistance spot and seam	
1060–0	A	A	A	E	A	A	A	B	Chemical equipment, railroad tank cars
H12	A	A	A	E	A	A	A	A	
H14	A	A	A	D	A	A	A	A	
H16	A	A	B	D	A	A	A	A	
H18	A	A	B	D	A	A	A	A	
1100–0	A	A	A	E	A	A	A	B	Sheet metal work, spun holloware, fin stock
H12	A	A	A	E	A	A	A	A	
H14	A	A	A	D	A	A	A	A	
H16	A	A	B	D	A	A	A	A	
H18	A	A	C	D	A	A	A	A	
1350–0	A	A	A	E	A	A	A	B	Electrical conductors
H12, H111	A	A	A	E	A	A	A	A	
H14, H24	A	A	A	D	A	A	A	A	
H16, H26	A	A	B	D	A	A	A	A	
H18	A	A	B	D	A	A	A	A	
2011–T3	D[c]	D	C	A	D	D	D	D	Screw-machine products
T4, T451	D[c]	D	B	A	D	D	D	D	
T8	D	B	D	A	D	D	D	D	
2014–0	—	—	—	D	D	D	D	B	Truck frames, aircraft structures
T3, T4, T451	D[c]	C	C	B	D	D	B	B	
T6, T651, T6510, T6511	D	C	D	B	D	D	B	B	
2017–T4, T451	D[c]	C	C	B	D	D	B	B	Screw-machine products, fittings

TABLE 4.38 Typical Characteristics and Applications of Wrought Aluminum (*Continued*)

Alloy and temper	Resistance to corrosion		Workability (cold)[e]	Machinability[e]	Brazability[f]	Weldability[f]			Some applications of alloy
	General[a]	Stress-corrosion cracking[b]				Gas	Arc	Resistance spot and seam	
2018–T61	—	—	—	B	—	—	—	—	Aircraft engine cylinders, heads, and pistons
2024–0	—	—	—	D	D	D	D	D	
T4, T3, T351, T3510, T3511	D[c]	C	C	B	D	C	B	B	
T361	D[c]	C	D	B	D	D	C	B	Truck wheels, screw-machine products, aircraft structures
T6	D	B	C	B	D	D	C	B	
T861, T81, T851, T8510									
T8511	D	B	D	B	D	D	C	B	
T72	—	—	—	B	—	—	—	—	
2025–T6	D	C	—	B	D	D	B	B	Forgings, aircraft propellers
2117–T4	C	A	B	C	D	D	B	B	
2218–T61	D	C	—	—	—	—	—	C	Jet engine impellers and rings
T72	D	C	—	B	D	D	C	B	
2618–T61	D	C	—	B	D	D	C	B	Aircraft engines
3003–0	A	A	A	E	A	A	A	A	Cooking utensils, chemical equipment, pressure vessels, sheet metal work, builder's hardware, storage tanks
H12	A	A	A	E	A	A	A	A	
H14	A	A	B	D	A	A	A	A	
H16	A	A	C	D	A	A	A	A	
H18	A	A	C	D	A	A	A	A	
H25	A	A	B	D	A	A	A	A	

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3004–0	A	A	A	D	B	B	A	B	
H32	A	A	B	D	B	B	A	A	
H34	A	A	B	C	B	B	A	A	Sheet metal work, storage tanks
H36	A	A	C	C	B	B	A	A	
H38	A	A	C	C	B	B	A	A	
3105–0	A	A	A	E	B	B	A	B	
H12	A	A	B	E	B	B	A	A	
H14	A	A	B	D	B	B	A	A	Residential siding, mobile homes, rain-carrying goods, sheet metal work
H16	A	A	C	D	B	B	A	A	
H18	A	A	C	D	B	B	A	A	
H25	A	A	B	D	B	B	A	A	
4032–T6	C	B	—	B	D	D	B	C	Pistons
5005–0	A	A	A	E	B	A	A	B	
H12	A	A	A	E	B	A	A	A	
H14	A	A	B	D	B	A	A	A	
H16	A	A	C	D	B	A	A	A	Appliances, utensils, architectural, electrical conductor
H18	A	A	C	D	B	A	A	A	
H32	A	A	A	E	B	A	A	A	
H34	A	A	B	D	B	A	A	A	
H36	A	A	C	D	B	A	A	A	
H38	A	A	C	D	B	A	A	A	
5050–0	A	A	A	E	B	A	A	B	
H32	A	A	A	D	B	A	A	A	
H34	A	A	B	D	B	A	A	A	Builder's hardware, refrigerator trim, coiled tubes
H36	A	A	C	C	B	A	A	A	
H38	A	A	C	C	B	A	A	A	
5052–0	A	A	A	D	C	A	A	B	
H32	A	A	B	D	C	A	A	A	
H34	A	A	B	C	C	A	A	A	Sheet metal work, hydraulic tube, appliances
H36	A	A	C	C	C	A	A	A	
H38	A	A	C	C	C	A	A	A	

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TABLE 4.38 Typical Characteristics and Applications of Wrought Aluminum (*Continued*)

Alloy and temper	Resistance to corrosion		Workability (cold)[e]	Machinability[e]	Brazability[f]	Weldability[f]			Some applications of alloy
	General[a]	Stress-corrosion cracking[b]				Gas	Arc	Resistance spot and seam	
5056–0	A[d]	B[d]	A	D	D	C	A	B	Cable sheathing, rivets for magnesium, screen wire, zippers
H111	A[d]	B[d]	A	D	D	C	A	A	
H12, H32	A[d]	B[d]	B	D	D	C	A	A	
H14, H34	A[d]	B[d]	B	C	D	C	A	A	
H18, H38	A[d]	C[d]	C	C	D	C	A	A	
H192	B[d]	D[d]	D	B	D	C	A	A	
H392	B[d]	D[d]	D	B	D	C	A	A	
5083–0	A[d]	B[d]	B	D	D	C	A	B	Unfired, welded pressure vessels, marine, auto aircraft cryogenics, TV towers, drilling rigs, transportation equipment, missile components
H321	A[d]	B[d]	C	D	D	C	A	A	
H111	A[d]	B[d]	C	D	D	C	A	A	
5086–0	A[d]	A[d]	A	D	D	C	A	B	
H32, H116, H117	A[d]	A[d]	B	D	D	C	A	A	
H34	A[d]	B[d]	B	C	D	C	A	A	
H36	A[d]	B[d]	C	C	D	C	A	A	
H38	A[d]	B[d]	C	C	D	C	A	A	
H111	A[d]	A[d]	B	D	D	C	A	A	
5154–0	A[d]	A[d]	A	D	D	C	A	B	Welded structures, storage tanks, pressure vessels, saltwater service
H32	A[d]	A[d]	B	D	D	C	A	A	
H34	A[d]	A[d]	B	C	D	C	A	A	
H36	A[d]	A[d]	C	C	D	C	A	A	
H38	A[d]	A[d]	C	C	D	C	A	A	
5252-H24	A	A	B	D	C	A	A	A	Automotive and appliance trim
H25	A	A	B	C	C	A	A	A	
H28	A	A	C	C	C	A	A	A	

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5454–0	A	A	A	D	D	C	A	B	Welded structures, pressure vessels, marine service
H32	A	A	B	D	D	C	A	A	
H34	A	A	B	C	D	C	A	A	
H111	A	A	B	D	D	C	A	A	
5456–0	A[d]	B[d]	B	D	D	C	A	B	High-strength welded structures, storage tanks, pressure vessels, marine applications
H111	A[d]	B[d]	C	D	D	C	A	A	
H321[g], H1116	A[d]	B[d]	C	D	D	C	A	A	
5457–0	A	A	A	E	B	A	A	B	Anodized automotive and appliance trim
5657–H241	A	A	A	D	B	A	A	A	
H25	A	A	B	D	B	A	A	A	
H26	A	A	B	D	B	A	A	A	
H28	A	A	C	D	B	A	A	A	
6005–T5	B	A	C	C	A	A	A	A	Heavy-duty structures requiring good corrosion resistance—truck and marine, railroad cars, furniture, pipelines
6053–0	—	—	—	E	A	A	A	B	Wire and rod for rivets
T6, T61	A	A	—	C	A	A	A	A	
6061–0	B	A	A	D	A	A	A	B	Heavy-duty structures requiring good corrosion resistance—truck and marine, railroad cars, furniture, pipelines
T4, T451, T4510, T4511	B	B	B	C	A	A	A	A	
T6, T651, T652, T6510, T6511	B	A	C	C	A	A	A	A	
6063–T1	A	A	B	D	A	A	A	A	Pipe railing, furniture architectural extrusions
T4	A	A	B	D	A	A	A	A	
T5, T52	A	A	B	C	A	A	A	A	
T6	A	A	C	C	A	A	A	A	
T83, T831, T832	A	A	C	C	A	A	A	A	

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TABLE 4.38 Typical Characteristics and Applications of Wrought Aluminum (*Continued*)

Alloy and temper	Resistance to corrosion: General[a]	Resistance to corrosion: Stress-corrosion cracking[b]	Work-ability (cold)[e]	Machin-ability[e]	Brazability[f]	Weldability[f]: Gas	Weldability[f]: Arc	Weldability[f]: Resistance spot and seam	Some applications of alloy
6151–T6, T652	—	—	—	—	—	—	—	—	Moderate strength intricate forgings for machine and automotive parts
6262–T6, T651, T6510, T6511	B	A	C	B	A	A	A	A	Screw-machine products
T9	B	A	D	B	A	A	A	A	
6463–T1	A	A	B	D	A	A	A	A	Extruded architectural and trim sections
T5	A	A	B	C	A	A	A	A	
T6	A	A	C	C	A	A	A	A	
7075–0	—	—	—	D	D	D	C	B	
T6, T651, T652, T6510, T6511	C[c]	C	D	B	D	D	C	B	Aircraft and other structures
T73, T7351	C	B	D	B	D	D	C	B	

[a] Ratings A through E are relative ratings in decreasing order of merit, based on exposures to sodium chloride solution by intermittent spraying or immersion. Alloys with A and B ratings can be used in industrial and seacoast atmospheres without protection. Alloys with C, D, and E ratings generally should be protected at least on faying surfaces.

[b] Stress-corrosion cracking ratings are based on service experience and on laboratory tests of specimens exposed to the 3.5% sodium chloride alternate immersion test.

A = No known instance of failure in service or in laboratory tests.
B = No known instance of failure in service; limited failures in laboratory tests of short transverse specimens.
C = Service failures with sustained tension stress acting in short transverse direction relative to grain structure; limited failures in laboratory tests of long transverse specimens.
D = Limited service failures with sustained longitudinal or long transverse stress.

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[c] In relatively thick sections the rating would be E.

[d] This rating may be different for material held at elevated temperature for long periods.

[e] Ratings A through E for workability (cold) and A through E for machinability are relative ratings in decreasing order of merit.

[f] Ratings A through D for weldability and brazability are relative ratings defined as follows:

A = Generally weldable by all commercial procedures and methods.

B = Weldable with special techniques or for specific applications which justify preliminary trials or testing to develop welding procedure and weld performance.

C = Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.

D = No commonly used welding methods have been developed.

[g] Material in this temper is not recommended for, and should not be used in, applications requiring exposure to sea water.

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1. Scope—This standard provides systems for designating wrought aluminum and wrought aluminum alloys, aluminum and aluminum alloys in the form of castings and foundry ingot, and the tempers in which aluminum and aluminum alloy wrought products and aluminum alloy castings are produced.

2. Wrought Aluminum and Aluminum Alloy Designation System (see Note 5.1)—A system of four-digit numerical designations is used to identify wrought aluminum and wrought aluminum alloys. The first digit indicates the alloy group as shown in Table 1. The last two digits identify the aluminum alloy or indicate the aluminum purity. The second digit indicates modifications of the original alloy or impurity limits.

2.1 Aluminum—In the 1xxx group for minimum aluminum purities of 99.00% and greater, the last two of the four digits in the designation indicate the minimum aluminum percentage (Note 5.2). These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage when it is expressed to the nearest 0.01%. The second digit in the designation indicates modifications in impurity limits. If the second digit in the designation is zero, it indicates that there is no special control on individual impurities; integers 1 through 9, which are assigned consecutively as needed, indicate special control of one or more individual impurities or alloying elements.

2.2 Aluminum Alloys—In the 2xxx through 8xxx alloy groups, the last two of the four digits in the designation have no special significance but serve only to identify the different aluminum alloys in the group. The second digit in the alloy designation indicates alloy modifications (Note 5.3). If the second digit in the designation is zero, it indicates the original alloy; integers 1 through 9, which are assigned consecutively, indicate alloy modifications.

2.3 Experimental Alloys—Experimental alloys are also designated in accordance with this system, but they are indicated by the prefix X. The prefix is dropped when the alloy is no longer experimental. During development and before they are designated as experimental, new alloys are identified by serial numbers assigned by their originators. Use of the serial number is discontinued when the X number is assigned.

2.4 National Variations—National variations (Note 5.4) of wrought aluminum and wrought aluminum alloys registered by another country in accordance with this system are identified by a serial letter (Note 5) before the numerical designation.

3. Cast Aluminum and Aluminum Alloy Designation System[1] (see Note 5.1)—A system of four-digit numerical designations is used to identify aluminum and aluminum alloys in the form of castings and foundry ingot. The first digit indicates the alloy group, as shown in Table 2. The second two digits identify the aluminum alloy or indicate the

[1] The castings and ingot alloy designation system described herein is not currently in use for some SAE cast aluminum alloys. It is applicable to Aluminum Association (AA) and American National Standard Institute (ANSI), and other, specification systems. Although the chemical composition limits shown in most SAE reports conform to the limits shown for comparable castings and ingots covered in AA and ANSI publications, the designation system described herein is not currently used in SAE Standards and Information Reports.

Figure 4.2 Alloy and temper designation systems for aluminum (SAE J993). (Report of Nonferrous Metals Committee, approved July 1967 and last revised September 1973. Conforms to American National Standard H35, 1-1972. Reaffirmed January 1989; reprinted with permission; copyright © 1992, Society of Automotive Engineers.)

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TABLE 1—DESIGNATION SYSTEM FOR WROUGHT ALUMINUM AND ALUMINUM ALLOY

Composition	Alloy No.
Aluminum, 99.0% min and greater	1xxx
Aluminum alloys grouped by major alloying element[a,b,c]	
Copper	2xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5xxx
Magnesium and silicon	6xxx
Zinc	7xxx
Other element	8xxx
Unused series	9xxx

[a] For codification purposes, an alloying element is any element which is intentionally added for any purpose other than grain refinement and for which minimum and maximum limits are specified.

[b] Standard limits for alloying elements and impurities are expressed to the following places:

Less than 1/1000%	0.000X
1/1000 up to 1/100%	0.00X
1/100 up to 1/10%	
Unalloyed aluminum made by a refining process	0.0XX
Alloys and unalloyed aluminum not made by a refining process	0.0X
1/10 through ½%	0.XX
Over ½%	0.X, X.X, etc.

[c] Standard limits for alloying elements and impurities are expressed in the following sequence: silicon; iron; copper; manganese; magnesium; chromium; nickel; zinc (Note 1); titanium; other elements (each); other elements (Total); aluminum (Note 2).

Note 1—Additional specified elements having limits are inserted in alphabetical order of their chemical symbols between zinc and titanium, or are specified in footnotes.

Note 2—Aluminum is specified as minimum for unalloyed aluminum, and as a remainder for aluminum alloys.

aluminum purity. The last digit, which is separated from the others by a decimal point, indicates the product form, that is, castings or ingot. A modification of the original alloy or impurity limits is indicated by a serial letter (Note 5.6) before the numerical designation.

3.1 Aluminum Castings and Ingot—In the 1xx.x group for minimum aluminum purities of 99.00% and greater, the second two of the four digits in the designation indicate the minimum aluminum percentage (Note 5.2).

These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage when it is expressed to the nearest 0.01%. The last digit, which is to the right of the decimal point, indicates the product form: 1xx.0 indicates castings, and 1xx.1 indicates ingot. Special control of one or more individual elements other than aluminum is indicated by a serial letter (Note 5.6) before the numerical designation.

3.2 Aluminum Alloy Castings and Ingot—In the 2xx.x through 9xx.x alloy groups, the second two of the four digits in the designation have no special significance but serve only to identify the different aluminum alloys in the group. The last digit, which is to the right of the decimal point, indicates the product form: xxx.0 indicates castings, xxx.1 indicates ingot which has chemical composition limits conforming to paragraph 3.2.1, and xxx.2 indicates ingot which has chemical com-

Figure 4.2 (*Continued*)

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TABLE 2—DESIGNATION SYSTEM FOR CAST ALUMINUM AND ALUMINUM ALLOY

Composition	Alloy No.
Aluminum, 99.00% min and greater	1xx.x
Aluminum alloy group by major alloying element[a,b,c]	
Copper	2xx.x
Silicon, with added copper and/or magnesium	3xx.x
Silicon	4xx.x
Magnesium	5xx.x
Zinc	7xx.x
Tin	8xx.x
Other element	9xx.x
Unused series	6xx.x

[a] For codification purposes, an alloying element is any element which is intentionally added for any purpose other than grain refinement and for which minimum and maximum limits are specified.

[b] Standard limits for alloying elements and impurities are expressed to the following places:

Less than 1/1000%	0.000X
1/1000 up to 1/100%	0.00X
1/100 up to 1/10%	
Unalloyed aluminum made by a refining process	0.0XX
Alloys and unalloyed aluminum not made by a refining process	0.0X
1/10 through ½%	0.XX
Over ½%	0.X, X.X, etc.

[c] Standard limits for alloying elements and impurities are expressed in the following sequence: silicon; iron; copper; manganese; magnesium; chromium; nickel; zinc (Note 1); titanium; other elements (each); other elements (Total); aluminum (Note 2).

Note 1—Additional specified elements having limits are inserted in alphabetical order of their chemical symbols between zinc and titanium, or are specified in footnotes.

Note 2—Aluminum is specified as minimum for unalloyed aluminum, and as a remainder for aluminum alloys.

position limits that differ but fall within the limits for xxx.1 ingot. Alloy modifications (Note 5.3) are indicated by a serial letter (Note 5.9) before the numerical designation.

3.2.1 Limits for alloying elements and impurities for xxx.1 ingot are the same as for the alloy in the form of castings, except for the limits noted in Table 3.

3.3 Experimental Alloys—Experimental alloys are also designated in accordance with this system, but they are indicated by the prefix X. The prefix is dropped when the alloy is no longer experimental. During development and before they are designated as experimental, new alloys are identified by serial numbers assigned by their originators. Use of the serial number is discontinued when the X number is assigned.

4. Temper Designation System—The temper designation system is used for all forms of wrought and cast aluminum and aluminum alloys except ingot. It is based on the sequences of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments; but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of ba-

Figure 4.2 (*Continued*)

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TABLE 3

Element, %	For Castings	For Ingot
Iron, max	Sand and permanent mold:	
	Up thru 0.15	0.03 less than castings
	Over 0.15 thru 0.25	0.05 less than castings
	Over 0.25 thru 0.6	0.10 less than castings
	Over 0.6 thru 1.0	0.2 less than castings
	Over 1.0	0.3 less than castings
	Die	
	Up thru 1.3	0.3 less than castings
	Over 1.3	1.1 maximum
Magnesium, min	All	
	Less than 0.50	0.05 more than castings°
	0.5 and greater	0.1 more than castings°
Zinc, max	Die	
	Over 0.25 thru 0.6	0.10 less than castings
	Over 0.6	0.1 less than castings

°Applicable only when the specified magnesium range for castings is greater than 0.15%.

sic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

4.1 Basic Temper Designations

F As Fabricated—Applies to the products of shaping processes in which no special control over thermal conditions or strain-hardening is employed. For wrought products, there are no mechanical property limits.

O Annealed (Wrought Products Only)—Applies to wrought products which are fully annealed to obtain the lowest strength condition.

H Strain Hardened (Wrought Products Only)—Applies to products which have their strength increased by strain-hardening, with or without supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits.

W Solution Heat-Treated—An unstable temper applicable only to alloys which spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is indicated; for example, W ½ h.

T Thermally Treated To Produce Stable Tempers Other Than **F, O,** or **H**—Applies to products which are thermally treated, with or without supplementary strain-hardening, to produce stable tempers. The T is always followed by one or more digits.

4.2 Subdivisions of Basic Tempers

4.2.1 Subdivisions of H Temper: Strain Hardened

4.2.1.1 The first digit following the H indicates the specific combination of basic operations, as follows:

H1 Strain Hardened Only—Applies to products which are strain hardened to obtain the desired strength without supplementary thermal treatment. The number following this designation indicates the degree of strain hardening.

H2 Strain Hardened and Partially Annealed—Applies to products which are strain hardened more than the desired final

Figure 4.2 (*Continued*)

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amount and then reduced in strength to the desired level by partial annealing. For alloys that age soften at room temperature, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H3 tempers. For other alloys, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H1 tempers and slightly higher elongation. The number following this designation indicates the degree of strain hardening remaining after the product has been partially annealed.

H3 STRAIN HARDENED AND STABILIZED—Applies to products which are strain hardened and whose mechanical properties are stabilized by a low-temperature thermal treatment which results in slightly lowered tensile strength and improved ductility. This designation is applicable only to those alloys which, unless stabilized, gradually age soften at room temperature. The number following this designation indicates the degree of strain hardening before the stabilization treatment.

4.2.1.2 The digit following the designations H1, H2, and H3 indicates the degree of strain hardening. Numeral 8 has been assigned to indicate tempers having an ultimate tensile strength equivalent to that achieved by a cold reduction (temperature during reduction not to exceed 120°F (49°C) of approximately 75% following a full anneal. Tempers between 0 (annealed) and 8 are designated by numerals 1 through 7. Material having an ultimate tensile strength about midway between that of the 0 temper and that of the 8 temper is designated by the numeral 4; about midway between the 0 and 4 tempers by the numeral 2; and about midway between the 4 and 8 tempers by the numeral 6. Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the 8 temper by 2.0 ksi (14 MPa) or more. For two-digit H tempers whose second digit is odd, the standard limits for ultimate tensile strength are exactly midway between those of the adjacent two-digit H tempers whose second digits are even.

NOTE: For alloys which cannot be cold reduced, an amount sufficient to establish an ultimate tensile strength applicable to the 8 temper (75% cold reduction after full anneal), the 6 temper tensile strength may be established by a cold reduction of approximately 55% following a full anneal, or the 4 temper tensile strength may be established by a cold reduction of approximately 35% after a full anneal.

4.2.1.3 The third digit (Note 10), when used, indicates a variation of a two-digit temper. It is used when the degree of control of temper or the mechanical properties are different from, but close to, those for the two-digit H temper designation to which it is added, or when some other characteristic is significantly affected. (See Appendix for three-digit H tempers.)

NOTE: The minimum ultimate tensile strength of a three-digit H temper is at least as close to that of the corresponding two-digit H temper as it is to the adjacent two-digit H tempers.

4.2.2 SUBDIVISIONS OF T TEMPER: THERMALLY TREATED

4.2.2.1 Numerals 1 through 10 following the T indicate specific sequences of basic treatments, as follows (Note 5.8):

T1 COOLED FROM AN ELEVATED TEMPERATURE SHAPING PROCESS AND NATURALLY AGED TO A SUBSTANTIALLY STABLE CONDITION—Applies to products for which the rate of cooling from an elevated temperature shaping process, such as casting or ex-

Figure 4.2 (*Continued*)

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trusion, is such that their strength is increased by room temperature aging.

T2 ANNEALED (CAST PRODUCTS ONLY)—Applies to cast products which are annealed to improve ductility and dimensional stability.

T3 SOLUTION HEAT TREATED AND THEN COLD WORKED—Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T4 SOLUTION HEAT TREATED AND NATURALLY AGED TO A SUBSTANTIALLY STABLE CONDITION—Applies to products which are not cold worked after solution heat treatment, or in which the effect or cold work in flattening or straightening may not be recognized in mechanical property limits.

T5 COOLED FROM AN ELEVATED TEMPERATURE SHAPING PROCESS AND THEN ARTIFICIALLY AGED—Applies to products which are cooled from an elevated temperature shaping process, such as casting or extrusion, and then artificially aged to improve mechanical properties or dimensional stability or both.

T6 SOLUTION HEAT TREATED AND THEN ARTIFICIALLY AGED—Applies to products which are not cold worked after solution heat treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T7 SOLUTION HEAT TREATED AND THEN STABILIZED—Applies to products which are stabilized to carry them beyond the point of maximum strength to provide control of some special characteristics.

T8 SOLUTION HEAT TREATED, COLD WORKED, AND THEN ARTIFICIALLY AGED—Applies to products which are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T9 SOLUTION HEAT TREATED, ARTIFICIALLY AGED, AND THEN COLD WORKED—Applies to products which are cold worked to improve strength.

T10 COOLED FROM AN ELEVATED TEMPERATURE SHAPING PROCESS, ARTIFICIALLY AGED, AND THEN COLD WORKED—Applies to products which are artificially aged after cooling from an elevated temperature shaping process, such as casting or extrusion, and then cold worked to improve strength further.

4.2.2.2 Additional digits (Note 5.9), the first of which shall not be zero, may be added to designations T1 through T10 to indicate a variation in treatment which significantly alters the characteristics of the product. (See Appendix for specific additional digits for T tempers.)

5. Notes

5.1 Producers of wrought aluminum and wrought aluminum alloys, and aluminum and aluminum alloy castings and foundry ingot, may register chemical composition limits and designations conforming to this standard with the Aluminum Association (AA) provided the aluminum or aluminum alloy is offered for sale, the complete chemical composition limits are registered, and the composition is significantly different from that of any aluminum or aluminum alloy for which a numerical designation already has been assigned. A numerical designation

Figure 4.2 (*Continued*)

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assigned in conformance with this standard should be used only to indicate an aluminum or aluminum alloy having chemical composition limits identical to those registered with AA for that aluminum or aluminum alloy.

5.2 The aluminum content for unalloyed aluminum made by a refining process is the difference between 100.000% and the sum of all other metallic elements present in amounts of 0.0010% or more each, expressed to the third decimal; for unalloyed aluminum not made by a refining process, it is the difference between 100.00% and the sum of all other metallic elements present in amounts of 0.010% or more each, expressed to the second decimal.

5.3 A modification of the original alloy is limited to any one or a combination of the following:

(a) Change of not more than the following amounts in the arithmetic mean of the limits for an alloying element:

Arithmetic Mean of Limits for Alloying Elements in Original Alloy, %	Maximum Change, %
Up thru 1.0	0.15
Over 1.0 thru 2.0	0.20
Over 2.0 thru 3.0	0.25
Over 3.0 thru 4.0	0.30
Over 4.0 thru 5.0	0.35
Over 5.0 thru 6.0	0.40
Over 6.0	0.50

To determine compliance when limits are specified for a combination of two or more elements in one alloy composition, the mean of such a combination should be compared to the sum of the mean values of the same individual elements, or any combination thereof, in another alloy composition.

(b) Addition or deletion of not more than one alloying element with limits having an arithmetic mean of not more than 0.30%.

(c) Substitution of one alloying element for another element serving the same purpose.

(d) Change in limits for impurities.

(e) Change in limits for grain refining elements.

(f) Distinctive iron or silicon limits, or both, reflecting high purity base metal.

An alloy shall not be registered as a modification if it meets the requirements for a national variation.

5.4 A national variation has composition limits which are similar but not identical to those registered by another country, with differences such as:

(a) Differences in the arithmetic mean of limits for alloying elements not exceeding the following amounts:

Arithmetic Mean of Limits for Alloying Elements in Original Alloy or Modification, %	Maximum Difference, %
Up thru 1.0	0.15
Over 1.0 thru 2.0	0.20
Over 2.0 thru 3.0	0.25
Over 3.0 thru 4.0	0.30
Over 4.0 thru 5.0	0.35
Over 5.0 thru 6.0	0.40
Over 6.0	0.50

Figure 4.2 (*Continued*)

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To determine compliance when limits are specified for a combination of two or more elements in one alloy composition, the mean of such a combination should be compared to the sum of the mean values of the same individual elements, or any combination thereof, in another alloy composition.

(b) Substitution of one alloying element for another element serving the same purpose.

(c) Different limits on impurities except for low iron. Low iron, reflecting high purity base metal, should be considered an alloy modification. See paragraph 5.3 (f).

(d) Different limits on grain refining elements.

(e) Inclusion of a minimum limit for iron or silicon, or both.

Wrought aluminum and wrought aluminum alloys meeting these requirements shall not be registered as a new alloy or alloy modification.

5.5 The serial letters are assigned internationally in alphabetical sequence starting with A but omitting I, O, and Q.

5.6 The serial letters are assigned in alphabetical sequence starting with A but omitting I, O, Q, and X, the X being reserved for experimental alloys.

5.7 Numerals 1 through 9 may be arbitrarily assigned as the third digit and registered with AA for an alloy and product to indicate a variation of a two-digit H temper provided the temper is used or is available for use by more than one user, mechanical property limits are registered, the characteristics of the temper are significantly different from those of all other tempers which have the same sequence of basic treatments and for which designations already have been assigned for the same alloy and product, and the following are also registered if characteristics other than mechanical properties are considered significant: (a) test methods and limits for the characteristics, or (b) the specific practices used to produce the temper. Zero has been assigned to indicate variations negotiated between the manufacturer and purchaser which are not used widely enough to justify registration.

5.8 A period of natural aging at room temperature may occur between or after the operations listed for tempers T3 through T10. Control of this period is exercised when it is metallurgically important.

5.9 Additional digits may be arbitrarily assigned and registered with AA for an alloy and product to indicate a variation of tempers T1 through T10 provided the temper is used or is available for use by more than one user; mechanical property limits are registered, the characteristics of the temper are significantly different from those of all other tempers which have the same sequence of basic treatments and for which designations already have been assigned for the same alloy and product, and the following are also registered if characteristics other than mechanical properties are considered significant: a. test methods and limits for the characteristics, or b. the specific practices used to provide the temper. Variations in treatment which do not alter the characteristics of the product are considered alternate treatments for which additional digits are not assigned.

APPENDIX

A1. Three-Digit H Tempers

A1.1 The following three-digit H temper designations have been assigned for wrought products in all alloys:

Figure 4.2 (*Continued*)

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H111 Applies to products which are strain hardened less than the amount required for a controlled H11 temper.

H112 Applies to products which acquire some temper from shaping processes not having special control over the amount of strain hardening or thermal treatment, but for which there are mechanical property limits.

A1.2 The following three-digit H temper designations have been assigned for wrought products in alloys containing over a nominal 4% magnesium.

H311 Applies to products which are strain hardened less than the amount required for a controlled H31 temper.

H321 Applies to products which are strain hardened less than the amount required for a controlled H32 temper.

H323 Applies to products which are specially fabricated to have
H343 acceptable resistance to stress corrosion cracking.

A1.3 The following three-digit H temper designations have been assigned for:

Patterned or Embossed Sheet	Fabricated from
H114	0 temper
H124, H224, H324	H11, H21, H31 temper, respectively
H134, H234, H334	H12, H22, H32 temper, respectively
H144, H244, H344	H13, H23, H33 temper, respectively
H154, H254, H354	H14, H24, H34 temper, respectively
H164, H264, H364	H15, H25, H35 temper, respectively
H174, H274, H374	H16, H26, H36 temper, respectively
H184, H284, H384	H17, H27, H37 temper, respectively
H194, H294, H394	H18, H28, H38 temper, respectively
H195, H295, H395	H19, H29, H39 temper, respectively

A2. Additional Digits for T Tempers

A2.1 The following specific additional digits have been assigned for stress-relieved tempers of wrought products:

T51 Stress Relieved by Stretching—Applies to the following products when stretched the indicated amounts after solution heat treatment or cooling from an elevated temperature shaping process.

Product	Stretch, Permanent Set, %
Plate	1.5-3
Rod, bar, shapes extruded tube	1-3
Drawn tube	0.5-3

Applies directly to plate and rolled or cold-finished rod and bar. These products receive no further straightening after stretching.

Applies to extruded rod, bar, shapes, and tube and to drawn tube when designated as follows:

T510 Products that receive no further straightening after stretching.

T511 Products that may receive minor straightening after stretching to comply with standard tolerances.

T52 Stress Relieved by Compressing—Applies to products which are stress relieved by compressing after solution heat treat-

Figure 4.2 (*Continued*)

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Materials: Physical Properties, Characteristics, and Uses

ment, or cooling from an elevated temperature shaping process to produce a permanent set of 1-5%.

T54 STRESS RELIEVED BY COMBINED STRETCHING AND COMPRESSING—Applies to die forgings which are stress relieved by restriking cold in the finish die.

A2.2 The following temper designations have been assigned for wrought products heat treated from O or F temper to demonstrate response to heat-treatment.

T42 SOLUTION HEAT TREATED FROM THE O OR F TEMPER—To demonstrate response to heat treatment, and naturally aged to a substantially stable condition.

T62 SOLUTION HEAT TREATED FROM THE O OR F TEMPER—To demonstrate response to heat treatment, and artificially aged.

Temper designations T42 and T62 may also be applied to wrought products heat treated from any temper by the user when such heat treatment results in the mechanical properties applicable to these tempers.

Figure 4.2 (*Continued*)

many applications in military and commercial aircraft, as well as in rockets and missiles (aerospace vehicles).

Magnesium is the eighth most abundant element in the earth's crust. The metal is obtained by electrolysis of fused magnesium chloride derived from brines, wells, and seawater. Magnesium is a silvery white, lightweight metal that is also fairly tough. It is one-third lighter than aluminum. The metal tarnishes in air and burns easily when in the finely divided state with a dazzling white flame. The specific gravity of magnesium is 1.738 g/cm^3, and its density is 0.063 lb/in^3. Caution must be used when handling magnesium because of its flammability in air. Water should not be used to extinguish a magnesium fire.

Table 4.49 lists the specifications of wrought magnesium alloys. Table 4.50 lists the physical properties and characteristics of magnesium cast alloys. Table 4.51 lists the strength requirements of extruded magnesium bar, rod, and shapes (ASTM B-107).

4.5 Titanium Alloys

Titanium alloys have a high strength-to-weight ratio. They are used as armor plate in modern war planes and propeller shafts, rigging, and other parts of ships where high strength and resistance to salt water are required. Titanium metal is produced by reducing titanium

(Text continued on page 242.)

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TABLE 4.39 Typical Physical Properties of Wrought Copper Alloys

Customary units

Copper or copper alloy UNS no.	Melting point, °F		Density[a]	Coefficient of thermal expansion[b]			Thermal conductivity[c]	Electrical resistivity[d]	Electrical conductivity[e]	Thermal capacity[f]	Modulus	
	Liquidus	Solidus		68–212°F	68–392°F	68–572°F					Elastic[g]	Rigid[h]
C10200	1981	—	.323	9.4	9.6	9.8	226	10.3	101	.092	17	6.4
C11000	1981	1949	.322	9.4	9.6	9.8	226	10.3	101	.092	17	6.4
C11100	1981	—	.322	9.4	9.6	9.8	224	10.3	101	.092	17	6.4
C11300	1981	—	.322	9.4	9.6	9.8	224	10.3	100	.092	17	6.4
C11400	1981	—	.322	9.4	9.6	9.8	224	10.4	100	.092	17	6.4
C11500	1981	—	.322	9.4	9.6	9.8	224	10.4	100	.092	17	6.4
C11600	1981	—	.322	9.4	9.6	9.8	224	10.4	99	.092	17	6.4
C12000	1981	—	.323	9.4	9.6	9.8	223	10.7	97	.092	17	6.4
C12200	1981	—	.323	9.4	9.5	9.8	196	12.2	85	.092	17	6.4
C14500	1960	1931[i]	.323	9.4	9.6	9.8	205	10.9	95	.092	17	6.4
C14700	1970	1953	.323	9.4	9.6	9.8	216	10.9	95	.092	17	6.4
C15000	1979	—	.323	9.4	9.6	9.8	212[k]	11.2[k]	93[k]	.092	17	6.4
C16200	1969	—	.321	9.4	9.6	9.8	208	11.9	87	.092	17	6.4
C17000	1800	1600	.298	9.3	9.4	9.9	—	47.2	22	—	19	7.3
C17200	1800	1600	.298	9.3	9.4	9.9	—	47.2	22	.100	19	7.3
C17500	1955	1885	.316	—	9.8	—	—	23.1	45	—	18	6.8
C17600	1930	1850	.316	—	9.8	—	—	19.0	50	—	18	6.8
C18400	1967	—	.321	9.4	9.6	9.8	187[k]	13.0[k]	80[k]	.092	19	7.2
C18700	1976	1947[j]	.323	9.4	9.6	9.8	218	10.6	98	.092	17	6.4
C19200	1983	—	.320	9.0	—	—	125	20.8	50	.092	17	6.4
C21000	1950	1920	.320	—	—	10.0	135	18.5	00	.090	17	6.4
C22000	1910	1870	.318	—	—	10.2	109	23.6	44	.090	17	6.4
C23000	1880	1810	.316	—	—	10.4	92	28.0	37	.090	17	6.4

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C24000	1830	1770	.313	—	—	10.6	81	32.4	32	.090	16	6.0
C26000	1750	1680	.308	—	—	11.1	70	37.0	28	.090	16	6.0
C26800	1710	1660	.306	—	—	11.3	67	38.4	27	.090	15	5.6
C27000	1710	1660	.306	—	—	11.3	67	38.4	27	.090	15	5.6
C33000	1720	1660	.307	—	—	11.2	67	39.9	26	.090	15	5.6
C33100	1720	1660	.307	—	—	11.2	67	39.9	26	.090	15	5.6
C34200	1670	1630	.306	—	—	11.3	67	39.9	26	.090	15	5.6
C34500	1650	1625	.305	—	—	11.4	69	39.9	26	—	10	—
C35000	1650	1630	.305	—	—	11.4	67	39.9	26	.090	14	5.3
C36000	1650	1630	.307	—	—	11.4	67	39.9	26	.090	14	5.3
C37700	1640	1620	.305	—	—	11.5	69	38.4	27	.090	15	5.6
C46400	1650	1630	.304	—	—	11.8	67	39.9	26	.090	15	5.6
C46500	1650	1630	.304	—	—	11.8	67	39.9	26	.090	15	5.6
C46600	1650	1630	.304	—	—	11.8	67	39.9	26	.090	15	5.6
C46700	1650	1630	.304	—	—	11.8	67	39.9	26	.090	15	5.6
C51000	1920	1750	.320	—	—	9.9	40	69.1	15	.090	16	6.0
C51100	1945	1785	.320	—	—	9.9	48	52.0	20	.090	16	6.0
C52100	1880	1620	.318	—	—	10.1	36	79.8	13	.090	16	6.0
C52400	1830	1550	.317	—	—	10.2	29	94.3	11	.090	16	6.0
C54400	1830	1700	.321	—	—	9.6	50	54.6	19	.090	15	5.6
C60800	1945	1920	.295	—	—	10.0	46	60.0	17	.090	17.5	6.6
C61300	1915	1905	.285	—	—	9.0	39	74.1	14	.090	17	6.4
C61400	1915	1905	.285	—	—	9.0	39	74.1	14	.090	17	6.4
C61800	1910	1900	.274	—	—	9.0	37	79.8	13	—	17	—
C62300	1910	1890	.274	—	9.0	9.4	31	79.8	13	—	16	—
C62400	1910	1895	.274	—	9.0	9.2	34	79.8	13	—	16	—
C63000	1930	1890	.274	—	9.0	9.4	22	138.0	8	.090	17	6.4
C64200	1840	1800	.278	—	—	10.0	26	113.0	8	.090	16	6.0
C65500	1880	1780	.308	—	—	10.0	21	148.0	7	.090	15	5.6
C67000	1710	1665	.282	—	—	11.0	14	86.4	12	—	15	—
C67300	1620	1555	.299	—	—	11.0	—	86.4	12	—	15	—
C67400	1625	1550	.292	—	—	11.0	58	86.4	12	—	14	—

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TABLE 4.39 Typical Physical Properties of Wrought Copper Alloys (*Continued*)

Customary units

Copper or copper alloy UNS no.	Melting point, °F		Density[a]	Coefficient of thermal expansion[b]			Thermal conductivity[c]	Electrical resistivity[d]	Electrical conductivity[e]	Thermal capacity[f]	Modulus	
	Liquidus	Solidus		68–212°F	68–392°F	68–572°F					Elastic[g]	Rigid[h]
C67500	1630	1590	.302	—	—	11.8	61	43.2	24	.090	15	5.6
C70600	2100	2010	.323	—	—	9.5	26	115.0	9	.090	18	6.8
C71000	2192	2066	.323	—	—	9.1	21	160.0	6	.090	20	7.5
C71500	2260	2140	.323	—	—	9.0	17	225.0	5	.090	22	8.3
C75200	2030	1960	.316	—	—	9.0	19	173.0	6	.090	18	6.8
C77000	1930	—	.314	—	—	9.3	17	189.0	6	.090	18	6.8

[a] lb/in^3 at 68°F.
[b] Per °F at temperature range indicated (multiply factor given by 10^{-6}).
[c] Btu/ft^2/ft·h·°F at 68°F.
[d] (Annealed) ohms (circular mil/ft) at 68°F.
[e] (Annealed) percent IACS at 68°F (volume basis).
[f] (Specific heat) Btu/lb/°F at 68°F.
[g] (Tension) psi (multiply factor given by 10^6).
[h] Psi (multiply factor given by 10^6).
[i] Small amount of tellurium-rich constituent remains liquid down to 1575°F.
[j] Small amount of lead-rich constituent remains liquid down to 619°F.
[k] After precipitation-hardening heat treatment.
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TABLE 4.40 Fabrication Properties, Other Characteristics, and Typical Uses of Copper

Copper or copper alloy UNS no.	Approximate relative suitability for being worked*		Best temperature for hot working, °C	Approximate relative suitability* for being joined by									Machinability‡	Type of chip†	Typical uses	Characteristics
										Resistance welding						
	Cold	Hot		Soldering	Brazing	Oxyacetylene welding	Carbon arc welding	Gas-shielded arc welding	Coated-metal arc welding	Spot	Seam	Butt				
C10200	E	E	760–870	E	E	F	F	G	NR	NR	NR	G	20	L	Thermal and electrical conductors, electronic parts, glass-to-metal seals.	Oxygen-free 100% minimum electrical conductivity, excellent ductility, high purity, no out gassing. Not subject to hydrogen embrittlement. Designated for use where processing involves heating in a reducing atmosphere.
C11000	E	E	760–870	E	G	NR	F	F	NR	NR	NR	G	20	L	Electrical wiring and components, radiator fins, gaskets, washers, cold-heading wire, water deflectors, heat plugs, clock cases, plating anodes, screen wire.	Minimum electrical conductivity 100%, highest electrical conductivity of any metal except silver, has very high ductility. Will embrittle when heated to redness in a reducing atmosphere.
C11100	E	E	760–870	E	G	NR	F	F	NR	NR	NR	G	20	L	Radiator fins.	Has a softening temperature higher than the silver bearing coppers and electrolytic tough pitch copper.

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TABLE 4.40 Fabrication Properties, Other Characteristics, and Typical Uses of Copper (*Continued*)

Copper or copper alloy UNS no.	Approximate relative suitability for being worked*		Best temperature for hot working, °C	Approximate relative suitability* for being joined by									Machinability‡	Type of chip†	Typical uses	Characteristics
										Resistance welding						
	Cold	Hot		Soldering	Brazing	Oxyacetylene welding	Carbon arc welding	Gas-shielded arc welding	Coated-metal arc welding	Spot	Seam	Butt				
C11300	E	E	760–780	E	G	NR	F	F	NR	NR	NR	G	20	L	Commutator bars, segments, collector rings and contacts, core and fin stock for radiators.	Minimum electrical conductivity 98%. Resistance to softening increased by presence of silver. Effect increases with increased silver added. Higher-silver-content copper used for continued exposure to somewhat higher temperature.
C11400	E	E	760–780	E	G	NR	F	F	NR	NR	NR	G	20	L		
C11500	E	E	760–870	E	G	NR	F	F	NR	NR	NR	G	20	L		
C11600	E	E	760–870	E	G	NR	F	F	NR	NR	NR	G	20	L		
C12000	E	E	760–870	E	E	G	G	E	NR	NR	NR	G	20	L	Electrical conductors, applications involving welding or brazing.	Regarded as an alternate to Copper UNS no. C10200. More resistant to embrittlement than Copper UNS no. C11000 high electrical conductivity.
C12200	E	E	760–870	E	E	G	G	E	NR	NR	NR	G	20	L	Tube, all types of hydraulic systems, fuel lines, vacuum lines, air conditioning, heat exchangers, anodes, air, gasoline, hydraulic, and oil lines, oil coolers, gauge lines.	Slightly improved mechanical properties. Electrical conductivity about 85%. Not subject to hydrogen embrittlement.

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C14500	E	E	760–845	E	E	F	F	G	NR	NR	NR	G	80	S	Forgings and screw machine parts requiring high electrical and thermal conductivity, furnace brazing. Electrical connectors, motor and switch parts, soldering coppers, and welding torch tips.	Free-machining copper, combined with high electrical conductivity (90–96%).
C14700	E	E	760–870	E	E	NR	NR	NR	NR	NR	NR	G	80	S	Transformer and circuit-breaker terminals, studs, bolts, nuts, and current-carrying parts requiring fine machining.	Free-machining copper, combined with high electrical conductivity (90–96%).
C15000	E	E	760–870	E	G	F	F	F	NR	NR	NR	G	20	L	Resistance welding electrodes. Miscellaneous current-carrying components at elevated temperatures.	Precipitation hardened. Combined high strength and conductivity and resistance to softening at elevated temperatures.
C16200	E	G	760–870	E	E	F	F	G	NR	NR	NR	G	20	L	Electrical contacts and terminals, signal relays. Hard temper used for spring contact in small apparatus and resistance welding electrodes.	Moderate high strength and high electrical conductivity.
C17000	G	G	705–775	G	G	NR	F	G	NR	NR	NR	G	20	L	Leaf springs, electrical contacts, coil springs and bellows requiring severe forming distributor breaker arm, welding tips, and welding wheels.	Copper Alloy UNS nos. C17000, C17200, C17500, and C17600 can develop the highest mechanical properties by heat treatment Complete range of properties.
C17200	G	G	705–775	G	G	NR	F	G	NR	NR	NR	G	20	L		
C17500	G	G	760–925	G	G	NR	F	G	NR	NR	NR	G	20	L		

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TABLE 4.40 Fabrication Properties, Other Characteristics, and Typical Uses of Copper (*Continued*)

Copper or copper alloy UNS no.	Approximate relative suitability for being worked*		Best temperature for hot working, °C	Approximate relative suitability* for being joined by								Machinability†	Type of chip†	Typical uses	Characteristics
									Resistance welding						
	Cold	Hot		Soldering	Brazing	Oxyacetylene welding	Carbon arc welding	Gas-shielded arc welding	Coated-metal arc welding	Spot	Seam	Butt			
C17600	G	G	760–925	G	G	NR	F	G	NR	NR	NR	G	20	L	Clips, welder tips, and wheels.	
C18400	E	E	900–925	G	G	NR	F	G	NR	NR	NR	G	20	L	Spot welding electrodes and wheels, flash welding dies, and commutator segments.	Precipitation hardened. Fairly high electrical conductivity. Resistance to softening at elevated temperatures.
C18700	G	NR	—	E	G	NR	NR	NR	NR	NR	NR	F	80	S	Screw machine parts requiring high electrical and thermal conductivity.	Free-machining copper, high electrical conductivity. Unsuited for hot working.
C19200	E	E	815–950	E	E	G		E	NR	NR	NR	G	20		Flexible hose, electrical terminals, fuse clips, gaskets, air-conditioning and heat-exchanger tubing.	Resistance to softening and also stress corrosion.
C21000	E	G	760–870	E	E	G	F	G	NR	NR	NR	G	20	L	Emblems, vitreous enamel base, ornamental trim, and jewelry.	Copper Alloy UNS nos. C21000, C22000, and C23000 are generally

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C22000	E	G	760–870	E	E	G	F	G	NR	NR	NR	G	20	L	Emblems, vitreous enamel base, ornamental trim, jewelry, expansion plugs, valve parts, escutcheon fasteners, and spring clips.	reddish in color, soft and malleable, higher annealing point than copper and slightly stronger and similar in corrosion resistance. Good for drawing and forming. Resistance to dezincification and season cracking is excellent.
C23000	E	G	790–900	E	E	G	F	G	NR	F	NR	G	30	L	Radiator parts, heat-exchanger tubes, tube bends.	
C24000	E	F	815–900	E	E	G	F	G	NR	F	NR	G	30	L	Bellows and water temperature switch housing, flexible hose, pump lines.	Color is light golden, strength and ductility continue to increase.
C26000	E	F	730–845	E	E	G	F	F	NR	G	NR	G	30	L	Radiator tanks and lock-seam tubes, header plates, reflectors, lamp bases, terminals, ground straps, baffles, ammeter shells and speedometer counter-weights, washers, wheel covers, trim, carburetor parts.	Color is brass yellow. Greatest ductility of the copper-zinc series. Strength is higher than any of the preceding copper-zinc alloys.
C26800	E	NR	—	E	E	G	F	F	NR	G	NR	G	30	L	Radiator cores and tanks, lamp fixtures, socket shells, eyelets, fasteners and grommets, hinges, locks, pins, rivets, screws, and springs.	Strength increases and ductility decreases, but is still very good.
C27000	E	NR	—	E	E	G	F	F	NR	G	NR	G	30	L		
C33000	E	NR	—	E	G	F	F	F	NR	F	NR	F	60	M	Tube carburetor parts, oil cooler tube, radiator and ornamental work, pump and power cylinders and liners.	Provides some degree of machinability, together with moderate cold-working properties.

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TABLE 4.40 Fabrication Properties, Other Characteristics, and Typical Uses of Copper (*Continued*)

Copper or copper alloy UNS no.	Approximate relative suitability for being worked*		Best temperature for hot working, °C	Approximate relative suitability* for being joined by									Machinability‡	Type of chip†	Typical uses	Characteristics
										Resistance welding						
	Cold	Hot		Soldering	Brazing	Oxyacetylene welding	Carbon arc welding	Gas-shielded arc welding	Coated-metal arc welding	Spot	Seam	Butt				
C33100	E	NR	—	E	G	NR	NR	NR	NR	NR	NR	F	70	M	Keys.	Intended for blanking, piercing, and machining.
C34200	E	NR	—	E	G	NR	NR	NR	NR	NR	NR	F	90	S	Clock plates and nuts, clock and watch backs, keys, gears, and wheels.	Provides increased machinability with moderate cold-working properties.
C34500	F	F	705–790	E	G	NR	NR	NR	NR	NR	NR	F	90	S	Screw-machine parts requiring roll threads, knurls, or staking operations.	Best combination of machinability and cold-working properties.
C35000	F	NR	—	E	G	NR	NR	NR	NR	NR	NR	F	70	M	Keys.	Intended for blanking, piercing, and machining.
C36000	NR	F	709–790	E	G	NR	NR	NR	NR	NR	NR	F	100	S	Automatic screw-machine parts and carburetor, magneto parts, radiator drums and other fittings, plugs, inserts, gears, pinions, locks.	The standard free-cutting brass and its machinability has become the standard by which other alloys are rated.
C37700	NR	E	650–815	E	G	NR	NR	NR	NR	NR	NR	F	80	S	Forgings and pressings of all kinds. Headings, air-conditioning tube fittings, convertible top hardware (latches, hinges, etc.), forged valve bodies.	Excellent hot-working properties and widely used as forging rod. At ordinary temperatures it is strong, hard, and free-cutting.

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C46400 C46500 C46600 C46700	F F F F	E E E E	650–815 650–815 650–815 650–815	E E E E	E E E E	G G G G	F F F F	F F F F	NR NR NR NR	G G G G	F F G F	G G G G	30 30 30 30	L L L L	Aircraft turnbuckle barrels and balls, cold headed parts, forgings, screw-machine parts, marine hardware, condenser plates, welding rod, nozzles, and fittings.	Excellent hot and fair cold-working properties of somewhat higher strength, good saltwater corrosion resistance.
C51000 C51100	E E	NR NR	— —	E E	E E	F F	G G	G G	F F	G G	F F	E E	20 20	L L	Springs, bearings, clips, contacts, switch parts, diaphragms, welding rod, thermostats, bellows, clutch disks, lock washers, fasteners.	C51000 and C52100 have a remarkable combination of strength, ductility and resilience, and fatigue resistance.
C52100 C52400	G G	NR NR	— —	E E	E E	F F	G G	G G	F F	G G	F F	E E	20 20	L L	Springs, clips, contacts, terminal wire and bushings, diaphragms, and bellows.	
C54400	G	NR	—	E	G	NR	NR	NR	NR	NR	NR	F	80	S	Bearings, bushings, gears, pinions, shafts, thrust washers, valve parts.	Free-cutting, good cold-working properties, also suitable for blanking, forming, and bending.
C60800	G	F	790–870	F	F	NR	—	G	G	G	G	G	20	—	Condenser, evaporator, and heat exchanger tubes, ferrules.	
C61300	G	G	785–925	F	F	NR	G	[§]	G	G	G	G	20	L	Gibs, wear strips, gears, bushings, nuts, bolts, and threaded members.	Good cold-working properties and corrosion resistance. High strength and ductility.
C61400	G	G	785–925	F	F	NR	G	[§]	G	G	G	G	20	L	Gibs, wear strips, gears, bushings, nuts, bolts, and threaded members.	Good cold-working properties and corrosion resistance. High strength and ductility.

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TABLE 4.40 Fabrication Properties, Other Characteristics, and Typical Uses of Copper (*Continued*)

Copper or copper alloy UNS no.	Approximate relative suitability for being worked*		Best temperature for hot working, °C	Approximate relative suitability* for being joined by									Machinability‡	Type of chip†	Typical uses	Characteristics
										Resistance welding						
	Cold	Hot		Soldering	Brazing	Oxyacetylene welding	Carbon arc welding	Gas-shielded arc welding	Coated-metal arc welding	Spot	Seam	Butt				
C61800	F	G	760–885	F	G	NR	—	G	G	G	G	G	40	—	Bushings, bearings, corrosion applications, welding rod.	
C62300	F	G	730–815	F	F	NR	G	§	G	G	G	G	30	L	Valve guides, spark plug inserts, gears, valve seat inserts, oil plugs, and shifter forks.	Good hot-working properties; high strength retained well at elevated temperatures; acid and oxidation resistant.
C62400	NR	E	720–775	F	F	NR	G	§	G	G	G	G	30	L	Valve guides, spark plug inserts, gears, valve seat inserts, oil plugs, shifter forks, wear strips, ball bearings, and hydraulic valve components.	Excellent hot-working, poor cold-working properties; heat treated for high mechanical properties.
C63000	NR	G	705–760	F	F	NR	G	§	G	G	G	G	20	L	Retractable landing gear, propeller gears, large valve seat inserts, spacer bearings, high-pressure pump components.	Very high mechanical properties in the heat-treated condition; difficult to cold work; good hot-working properties, excellent corrosion resistance.
C64200	NR	E	705–760	F	F	NR	—	F	F	F	F	F	60	—	Valve stems, gears, bolts, nuts, valve bodies, and components.	Free machining, high strength, high corrosion resistance.

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C65500	E	E	705–760	G	E	G	G	E	F	E	E	E	30	L	Hydraulic pressure lines, bolts, clamps, piston rings, rivets, and shafting.	Relatively high strength, marked ductility and capability for being both hot- and cold-worked and joined by all procedures. Excellent corrosion resistance
C67000	NR	E	565–745	NR	F	NR	NR	§	G	G	F	G	30	S	Diesel injector nozzles; high pressure hydraulic applications, cams, pistons, and other components involving high mechanical loads and sliding contact.	High strength and good wear-resistant properties.
C67300	F	E	625–745	NR	G	NR	NR	NR	NR	NR	NR	F	70	S	Forged water pump impellers; gears, axial piston pump components, bushings, and bearings.	Hot-forgeable, free-cutting alloy having fairly high strength and good corrosion-resistant properties.
C67400	F	E	565–745	NR	F	NR	NR	§	G	G	F	G	30	L	Connecting rods, transmission synchronizing stop ring, door striker plates, shifter shoes, differential idler pins, forged water pump impellers, axial piston pump parts, bushings, and bearings.	Hot-forgeable, high-strength alloy with good wear-resistant properties and good corrosion resistance.
C67500	NR	E	625–790	E	E	G	F	F	NR	G	F	G	30	L	Clutch disks, pump rods, shafting, balls, valve stems, and bodies.	Strong, rigid, and abrasion resistant; adopted to hot forging and pressing, hot heading, and upsetting.

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TABLE 4.40 Fabrication Properties, Other Characteristics, and Typical Uses of Copper (*Continued*)

Copper or copper alloy UNS no.	Approximate relative suitability for being worked*		Best temperature for hot working, °C	Approximate relative suitability* for being joined by									Machinability‡	Type of chip†	Typical uses	Characteristics
										Resistance welding						
	Cold	Hot		Soldering	Brazing	Oxyacetylene welding	Carbon arc welding	Gas-shielded arc welding	Coated-metal arc welding	Spot	Seam	Butt				
C70600	G	G	760–980	E	E	F	NR	E	G	G	G	E	20	L	Condenser and heat-exchanger tubes.	Used where requirements are severe. Strong, tough, and very resistant to general corrosion as well as stress-corrosion cracking; also serviceable at higher temperatures than copper and brasses. Well suited for condenser and heat exchanger tube.
C71000	G	G	760–980	E	E	G	NR	E	E	E	E	E	20	L	Condenser and heat-exchanger tubes, ferrules.	Copper Alloy UNS nos. C71000 and C71500 are used where requirements are severe. Strong, tough, and very resistant to general corrosion as well as stress-corrosion cracking; also serviceable at higher temperatures than copper and brasses. Well suited for condenser and heat-exchanger tube.
C71500	G	G	925–1035	E	E	G	NR	E	E	E	E	E	20	L	Automatic oil coolers, heat-exchanger tubes.	

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C75200	E	NR	—	E	E	G	NR	F	NR	G	F	G	20	L	Rivets, screws, name plates, radio dials, etching stock, trim.	Copper Alloy UNS nos. C75200 and C77000 are manufactured in a wide range of nickel contents. Higher the nickel, the more silver white the alloy. 65% copper alloys have good cold-working properties and are used for cold drawing, spinning, forming, and stamping. The lower-copper-content
C77000	G	NR	—	E	E	G	NR	F	NR	G	F	G	30	L	Springs, resistance wire.	

* E = Excellent; G = Good; F = Fair; NR = Not recommended.
† S = Short; M = Medium; L = Long.
‡ Approximate relative machinability rating (free-cutting brass = 100).
§ Consumable electrode excellent. Tungsten are good, with ac preferred.
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TABLE 4.41 Mechanical Properties of Cast Copper Alloys

Copper alloy UNS no.*	SAE suffix†,§	ASTM standard no.	Casting method‡,§ and condition	Tensile strength, min		Yield strength, min		Elongation, min, % in 50 mm (2 in)
						MPa	ksi	
						0.5% ext. under load		
				MPa	ksi			
C83600	A	B271, B584	Sand, centrifugal	205	30	95	14	20
C83600	B	B505	Continuous	250	36	130	19	15
C83600	C		Continuous	345	50	170	15	12
C83800	A	B271, B584	Sand, centrifugal	205	30	90	13	20
C83800	B	B505	Continuous	205	30	95	15	16
C85200		B271, B584	Sand, centrifugal	240	35	85	12	25
C85400		B271, B584	Sand, centrifugal	205	30	75	11	20
						0.2% Offset		
C85800		B176	Die¶	380	55	205	30	15
C86200		B271, B505, B584	Sand, centrifugal, cont.	620	90	310	45	18
C86300	A	B271, B584	Sand, centrifugal	760	110	415	60	12
C86300	B	B505	Continuous	760	110	425	62	14
C86500	A	B271, B584	Sand, centrifugal	450	65	170	25	20
C86500	B	B505	Continuous	485	70	170	25	25
						0.5% Ext. Under Load		
C87200		B271, B584	Sand, centrifugal	310	45	125	18	20
C87400		B271, B584	Sand, centrifugal	345	50	145	21	18
C87500		B271, B584	Sand, centrifugal	415	60	165	24	16
						0.2% Offset		
C87800		B176	Die¶	585	85	345	50	25
C87900		B176	Die¶	485	70	240	35	25

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						0.5% Ext. Under Load		
C90300	A	B271, B584	Sand, centrifugal	275	40	125	18	20
C90300	B	B505	Continuous	305	44	150	22	18
C90500	A	B271, B584	Sand, centrifugal	275	40	125	18	20
C90500	B	B505	Continuous	305	44	170	25	10
C90700	A		Sand	240	35	125	18	10
C90700	B	B505	Continuous	275	40	170	25	10
C92200	A	B271, B584	Sand, centrifugal	235	34	110	16	24
C92200	B	B505	Continuous	260	38	130	19	18
C92300	A	B271, B584	Sand, centrifugal	250	36	110	16	18
C92300	B	B505	Continuous	275	40	130	19	16
C92500	A		Sand	240	35	125	18	10
C92500	B	B505	Continuous	275	40	165	24	10
C92700	A		Sand	240	35	125	18	10
C92700	B	B505	Continuous	260	38	140	20	8
C92900		B247, B505	Sand, continuous	310	45	170	25	8
C93200	A	B271, B584	Sand, centrifugal	205	30	95	14	15
C93200	B	B505	Continuous	240	35	140	20	10
C93500	A	B271, B584	Sand, centrifugal	195	28	85	12	15
C93500	B	B505	Continuous	205	30	110	16	12
C93700	A	B271, B584	Sand, centrifugal	205	30	85	12	15
C93700	B	B505	Continuous	240	35	140	20	6
C93700	C		Continuous	275	40	170	25	6
C93800	A	B271, B584	Sand, centrifugal	180	26	95	14	12
C93800	B	B505	Continuous	170	25	110	16	5
C94300	A	B271, B584	Sand, centrifugal	145	21	—	—	10
C94300	B	B505	Continuous	145	21	95	15	7
C94700	A	B505, B584	Sand, continuous	310	45	140	20	25
C94700	B	B505, B584	Sand, continuous (HT)	515	75	345	50	5
C94800		B505, B584	Sand, continuous	275	40	140	20	20

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TABLE 4.41 Mechanical Properties of Cast Copper Alloys (*Continued*)

Copper alloy UNS no.*	SAE suffix†,§	ASTM standard no.	Casting method‡,§ and condition	Tensile strength, min		Yield strength, min		Elongation, min, % in 50 mm (2 in)
						MPa	ksi	
						0.5% ext. under load		
				MPa	ksi			
C95200	A	B148, B271	Sand, centrifugal	450	65	170	25	20
C95200	B	B505	Continuous	470	68	180	26	20
C95300	A	B148, B271	Sand, centrifugal	450	65	170	25	20
C95300	B	B505	Continuous	485	70	180	26	25
C95300	C	B148, B271, B505	Sand, centrifugal, cont. (HT)	550	80	275	40	12
C95400	A	B148, B271	Sand, centrifugal	515	75	205	30	12
C95400	B	B505	Continuous	585	85	220	32	12
C95400	C	B148, B271	Sand, centrifugal (HT)	620	90	310	45	6
C95400	D	B505	Continuous (HT)	655	95	310	45	10
C95500	A	B148, B271	Sand, centrifugal	620	90	275	40	6
C95500	B	B505	Continuous	655	95	290	42	10
C95500	C	B148, B271	Sand, centrifugal (HT)	760	110	415	60	5
C95500	D	B505	Continuous (HT)	760	110	425	62	8
C95800	A	B148, B271	Sand, centrifugal	585	85	240	35	15
C95800	B	B505	Continuous (3)	620	90	260	38	18
C96200		B369	Sand	310	45	170	25	20

* Unified Numbering System. For cross-reference to SAE, former SAE, former ASTM, and former trade names, see SAE Information Report for Wrought and Cast Copper Alloys, SAE J461.

† Suffix symbols may be specified to distinguish between two or more sets of mechanical properties, heat treatment, conditions, etc. as applicable.

‡ All alloys listed are in the "as cast" condition except those designated as heat treated (HT) and copper alloy UNS No. C95800 which is temper annealed.

§ Most commonly used method of casting is shown for each alloy. However, unless the purchaser specifies the method of casting or the mechanical properties by supplement to the UNS number, the supplier may use any method which will develop the properties indicated.

¶ Mechanical properties shown for die castings are typical, not minimum.

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TABLE 4.42 Typical Physical Properties of Cast Copper Alloys (Customary Units)

Copper alloy UNS no.	Melting point. °F		Density, lb/in^3	Specific gravity	Coefficient of thermal expansion, 10^6 in/in/°F	Thermal conductivity, % of Cu*	Electrical conductivity, % IACS†	Modulus of elasticity, 10^6 psi
	Liquidus	Solidus			(20–400°F)			
C83600	1840	1570	0.318	8.83	10.0	18	15	14
C83800	1840	1550	0.312	8.60	10.0	18	15	13
C85200	1725	1700	0.307	8.50	11.5	21	18	11
C85400	1725	1700	0.305	8.45	11.2	23	20	12
C85800	1650	1600	0.305	8.40	12.0	—	20	15
C86200	1725	1650	0.288	7.85	12.0	9	8	15
C86300	1690	1625	0.283	7.84	12.0	9	8	14
C86500	1620	1585	0.301	8.30	11.3	22	22	15
C87200	1780	1580	0.302	8.40	9.2	7	6	15
C87400	1680	1510	0.300	8.27	10.9	7	7	15
C87500	1680	1510	0.300	8.27	10.9	7	7	15
C87800	1680	1510	0.300	8.27	10.9	7	7	20
C87900	1700	1650	0.308	8.50	12.0	—	15	15
C90300	1830	1570	0.318	8.70	10.0	19	12	15
C90500	1830	1570	0.315	8.72	11.0	19	11	15
C90700	1830	1528	0.317	8.78	10.2	19	10	14
C92200	1810	1520	0.312	8.65	10.0	18	14	14
C92300	1830	1570	0.317	8.80	10.0	19	12	14
C92500	1830	1570	0.317	8.85	10.0	—	11	13
C92700	1800	1550	0.317	8.80	10.1	12	11	13

TABLE 4.42 Typical Physical Properties of Cast Copper Alloys (Customary Units) (*Continued*)

Copper alloy UNS no.	Melting point, °F		Density, lb/in^3	Specific gravity	Coefficient of thermal expansion, 10^6 in/in/°F	Thermal conductivity, % of Cu*	Electrical conductivity, % IACS†	Modulus of elasticity, 10^6 psi
	Liquidus	Solidus			(20–400°F)			
C92900	1880	1575	0.320	8.79	9.5	15	9	14
C93200	1800	1570	0.322	8.93	10.0	15	12	14
C93500	1830	1570	0.320	8.87	10.0	18	15	14.5
C93700	1705	1400	0.320	8.95	10.3	12	10	11
C93800	1730	1570	0.334	9.25	10.3	13	12	10
C94300	1750	1650	0.336	9.29	10.0	16	9	11
C94700	1880	1660	0.320	8.80	11.0	14	12	15
C94700 (HT)	1880	1660	0.320	8.80	11.0	15	15	15
C94800	1880	1660	0.320	8.80	11.0	10	12	15
C95200	1913	1907	0.276	7.64	9.0	13	11	15
C95300	1913	1904	0.272	7.53	9.0	16	15	16
C95300 (HT)	1913	1904	0.272	7.53	9.0	16	13	15
C95400	1900	1880	0.269	7.45	9.0	15	13	15.5
C95400 (HT)	1900	1880	0.269	7.45	9.2	15	12	16
C95500	1930	1900	0.272	7.53	9.0	11	8.5	16
C95500 (HT)	1930	1900	0.272	7.53	9.0	11	8	17
C95800	1940	1910	0.276	7.64	9.0	9	7	16.5
C96200	2100	2010	0.323	8.94	9.5	11	11	18

* Cu = 226 Btu/ft^2/ft/h/°F at 68°F.

† International annealed copper standard.

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TABLE 4.43 Tensile Strength Requirements and Approximate Rockwell Hardness Values for Rolled Tempers

Rolled temper		Tensile strength, ksi*		Tensile strength, MPa†		Approximate Rockwell hardness‡							
						B scale				Superficial 30-T			
Temper designation						0.020 (0.508) to 0.036 in (0.914 mm) incl		Over 0.036 in (0.914 mm)		0.012 (0.305) to 0.028 in (0.711 mm) incl		Over 0.028 in (0.711 mm)	
Standard	Former	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Copper Alloy UNS No. C21000													
M20	As hot rolled	32	42	220	290	—	—	—	—	—	—	—	—
H01	Quarter hard	37	47	255	325	20	48	24	52	34	51	37	54
H02	Half hard	42	52	290	355	40	56	44	60	46	57	48	59
H03	Three-quarter hard	46	56	315	385	50	61	53	64	52	60	54	62
H04	Hard	50	59	345	405	57	64	60	67	57	62	59	64
H06	Extra hard	56	64	385	440	64	70	66	72	62	66	63	67
H08	Spring	60	68	415	470	68	73	70	75	64	68	65	69
H10	Extra spring	61	69	420	475	69	74	71	76	65	69	66	70
Copper Alloy UNS No. C22000													
M20	As hot rolled	33	43	230	295	—	—	—	—	—	—	—	—
H01	Quarter hard	40	50	275	345	27	52	31	56	34	51	37	54
H02	Half hard	47	57	325	395	50	63	53	66	50	59	52	61
H03	Three-quarter hard	52	62	355	425	59	68	62	71	55	62	58	64
H04	Hard	57	66	395	455	65	72	68	75	60	65	62	67
H06	Extra hard	64	72	440	495	72	77	74	79	64	68	66	69
H08	Spring	69	77	475	530	76	79	78	81	67	69	68	70
H10	Extra spring	72	80	495	550	78	81	80	83	68	70	69	71

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TABLE 4.43 Tensile Strength Requirements and Approximate Rockwell Hardness Values for Rolled Tempers (*Continued*)

Rolled temper		Tensile strength, ksi*		Tensile strength, MPa†		Approximate Rockwell hardness‡							
						B scale				Superficial 30-T			
Temper designation						0.020 (0.508) to 0.036 in (0.914 mm) incl		Over 0.036 in (0.914 mm)		0.012 (0.305) to 0.028 in (0.711 mm) incl		Over 0.028 in (0.711 mm)	
Standard	Former	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Copper Alloy UNS No. C22600													
H01	Quarter hard	42	52	290	355	29	58	29	58	39	58	39	58
H02	Half hard	48	58	330	400	52	68	52	68	54	64	54	64
H03	Three-quarter hard	53	63	365	435	61	73	61	73	59	68	59	68
H04	Hard	58	67	400	460	67	77	67	77	64	70	64	70
H06	Extra hard	65	73	450	505	74	81	74	81	68	73	68	73
H08	Spring	70	78	485	540	78	83	78	83	71	74	71	74
H10	Extra spring	74	82	510	565	81	86	81	86	73	76	73	76
Copper Alloy UNS No. C23000													
M20	As hot rolled	37	47	255	325	—	—	—	—	—	—	—	—
H01	Quarter hard	44	54	305	370	33	58	37	62	42	57	45	60
H02	Half hard	51	61	350	420	56	68	59	71	56	64	58	66
H03	Three-quarter hard	57	67	395	460	66	73	69	76	63	68	65	70
H04	Hard	63	72	435	495	72	78	74	80	67	71	68	72
H06	Extra hard	72	80	495	550	78	83	80	85	70	74	71	75
H08	Spring	78	86	540	595	82	85	84	87	74	76	75	77
H10	Extra spring	82	90	565	620	84	87	86	89	75	77	76	78

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Copper Alloy UNS No. C24000													
M20	As hot rolled	41	51	285	350	—	—	—	—	—	—	—	—
H01	Quarter hard	48	58	330	400	38	61	42	65	42	57	45	60
H02	Half hard	55	65	380	450	59	70	62	73	56	64	58	66
H03	Three-quarter hard	61	71	420	490	69	76	72	79	63	68	65	70
H04	Hard	68	77	470	530	76	82	78	84	68	72	69	73
H06	Extra hard	78	87	540	600	83	87	85	89	72	75	73	76
H08	Spring	85	93	585	640	87	90	89	92	75	77	76	78
H10	Extra spring	89	97	615	670	88	91	90	93	76	78	77	79
Copper Alloy UNS No. C26000													
M20	As hot rolled	41	51	285	350	—	—	—	—	—	—	—	—
H01	Quarter hard	49	59	340	405	40	61	44	65	43	57	46	60
H02	Half hard	57	67	395	460	60	74	63	77	56	66	58	68
H03	Three-quarter hard	64	74	440	510	72	79	75	82	65	70	67	72
H04	Hard	71	81	490	560	79	84	81	86	70	73	71	74
H06	Extra hard	83	92	570	635	85	89	87	91	74	76	75	77
H08	Spring	91	100	625	690	89	92	90	93	76	78	76	78
H10	Extra spring	95	104	655	715	91	94	92	95	77	79	77	79
Copper Alloy UNS No. C26800													
M20	As hot rolled	40	50	275	345	—	—	—	—	—	—	—	—
H01	Quarter hard	49	59	340	405	40	61	44	65	43	57	46	60
H02	Half hard	55	65	380	450	57	71	60	74	54	64	56	66
H03	Three-quarter hard	62	72	425	495	70	77	73	80	65	69	67	71
H04	Hard	68	78	470	540	76	82	78	84	68	72	69	73
H06	Extra hard	79	89	545	615	83	87	85	89	73	75	74	76
H08	Spring	86	95	595	655	87	90	89	92	75	77	76	78
H10	Extra spring	90	99	620	685	88	91	90	93	76	78	77	79

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TABLE 4.43 Tensile Strength Requirements and Approximate Rockwell Hardness Values for Rolled Tempers (*Continued*)

Rolled temper		Tensile strength, ksi*		Tensile strength, MPa†		Approximate Rockwell hardness‡							
						B scale				Superficial 30-T			
Temper designation						0.020 (0.508) to 0.036 in (0.914 mm) incl		Over 0.036 in (0.914 mm)		0.012 (0.305) to 0.028 in (0.711 mm) incl		Over 0.028 in (0.711 mm)	
Standard	Former	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Copper Alloy UNS No. C27200													
M20	As hot rolled	41	51	285	350	—	—	—	—	—	—	—	—
H01	Quarter hard	49	59	340	405	40	61	44	65	43	57	46	60
H02	Half hard	56	66	385	455	57	74	60	76	54	67	56	68
H03	Three-quarter hard	63	73	435	505	71	78	74	81	64	70	66	71
H04	Hard	70	80	485	550	76	82	78	84	67	72	68	73
H06	Extra hard	81	91	560	625	82	87	85	89	71	75	72	76
Copper Alloy UNS No. C28000													
M20	As hot rolled	40	55	275	380	—	—	—	—	—	—	—	—
H01	Quarter hard	50	62	345	425	40	65	45	70	45	65	45	70
H02	Half hard	58	70	400	485	50	75	52	80	50	70	50	75
H03	Three-quarter hard	60	75	415	515	55	80	55	82	52	78	55	80
H04	Hard	70	85	485	585	60	85	60	87	55	80	55	82
H06	Extra hard	82	95	565	655	65	92	65	90	60	85	60	85

NOTE: Plate is generally available in only the as hot-rolled (M20) temper. Required properties for other tempers shall be agreed upon between the manufacturer and the purchaser at the time of placing the order.

* ksi = 1000 psi.

† MPa (megapascals).

‡ Rockwell hardness values apply as follows: the B scale values apply to metal 0.020 in (0.508 mm) and over in thickness, and the 30-T scale values apply to metal 0.012 in (0.305 mm) and over in thickness.

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TABLE 4.44 Tensile Strength Requirements and Approximate Rockwell Hardness Values

Temper designation†			Tensile strength, ksi* (MPa)		Approximate Rockwell hardness	
Standard	Former	Thickness, in (mm)	Min	Max	B scale	Superficial 30-T
		Copper Alloy UNS No. C51000				
M20	As hot rolled	Over 0.188 (4.775)	40 (275)	60 (415)	—	—
O60	Soft	Over 0.039 (0.991)	43 (295)	58 (400)	16–64	—
		Over 0.029 (0.737)			—	32–59
		Over 0.020 (0.508) to 0.039 (0.991) incl			12–60	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	24–53
		0.003 (0.076) to 0.010 (0.254) incl				
H02	Half hard	Over 0.039 (0.991)	58 (400)	73 (505)	64–85	—
		Over 0.029 (0.737)			—	59–73
		Over 0.020 (0.508) to 0.039 (0.991) incl			60–82	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	53–69
		0.003 (0.076) to 0.010 (0.254) incl				
H04	Hard	Over 0.039 (0.991)	76 (525)	91 (625)	86–93	—
		Over 0.029 (0.737)			—	73–78
		Over 0.020 (0.508) to 0.039 (0.991) incl			84–91	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	71–75
		0.003 (0.076) to 0.010 (0.254) incl				
H06	Extra hard	Over 0.039 (0.991)	88 (605)	103 (710)	92–96	—
		Over 0.029 (0.737)			—	77–81
		Over 0.020 (0.508) to 0.039 (0.991) incl			89–95	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	74–78
		0.003 (0.076) to 0.010 (0.254) incl				
H08	Spring	Over 0.039 (0.991)	95 (655)	110 (760)	94–98	—
		Over 0.029 (0.737)			—	79–82
		Over 0.020 (0.508) to 0.039 (0.991) incl			92–97	—

TABLE 4.44 Tensile Strength Requirements and Approximate Rockwell Hardness Values (*Continued*)

Temper designation†			Tensile strength, ksi* (MPa)		Approximate Rockwell hardness	
Standard	Former	Thickness, in (mm)	Min	Max	B scale	Superficial 30-T
		Copper Alloy UNS No. C51000 (*Continued*)				
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	76–80
		0.003 (0.076) to 0.010 (0.254) incl				
H10	Extra spring	Over 0.039 (0.991)	100 (690)	114 (790)	95–99	—
		Over 0.029 (0.737)			—	80–83
		Over 0.020 (0.508) to 0.039 (0.991) incl			94–98	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	77–81
		0.003 (0.076) to 0.010 (0.254) incl				
		Copper Alloy UNS Nos. C51100, C53200, C53400, and C54400				
M20	As hot rolled	Over 0.188 (4.775)	40 (275)	58 (415)	—	—
O60	Soft	Over 0.039 (0.991)	40 (275)	55 (380)	7–50	—
		Over 0.029 (0.737)			—	24–50
		Over 0.020 (0.508) to 0.039 (0.991) incl			0–45	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	16–46
H02	Half hard	Over 0.039 (0.991)	55 (380)	70 (485)	60–81	—
		Over 0.029 (0.737)			—	57–73
		Over 0.020 (0.508) to 0.039 (0.991) incl			53–78	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	52–71
H04	Hard	Over 0.039 (0.991)	72 (495)	87 (600)	82–90	—
		Over 0.029 (0.737)			—	71–77
		Over 0.020 (0.508) to 0.039 (0.991) incl			80–88	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	69–75
H06	Extra hard	Over 0.039 (0.991)	84 (580)	99 (685)	88–94	—
		Over 0.029 (0.737)			—	75–80

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		Over 0.020 (0.508) to 0.039 (0.991) incl			86–92	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	73–78
H08	Spring	Over 0.039 (0.991)	91 (625)	105 (720)	90–96	—
		Over 0.029 (0.737)			—	77–81
		Over 0.020 (0.508) to 0.039 (0.991) incl			88–94	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	75–79
H10	Extra spring	Over 0.039 (0.991)	96 (660)	109 (750)	92–97	—
		Over 0.029 (0.737)			—	78–82
		Over 0.020 (0.508) to 0.039 (0.991) incl			89–94	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	76–80
		Copper Alloy UNS No. C51900				
O60	Soft	Over 0.039 (0.991)	48 (330)	63 (435)	22–66	—
		Over 0.029 (0.737)			—	35–64
		Over 0.020 (0.508) to 0.039 (0.991) incl			18–63	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	25–57
H02	Half hard	Over 0.039 (0.991)	64 (440)	79 (545)	70–88	—
		Over 0.029 (0.737)			—	63–76
		Over 0.020 (0.508) to 0.039 (0.991) incl			65–85	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	58–72
H04	Hard	Over 0.039 (0.991)	80 (550)	96 (660)	89–95	—
		Over 0.029 (0.737)			—	74–80
		Over 0.020 (0.508) to 0.039 (0.991) incl			86–93	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	72–78
		Copper Alloy UNS No. C52100				
M20	As hot rolled	Over 0.188 (4.775)	50 (345)‡	78 (485)	—	—
O60	Soft	Over 0.039 (0.991)	53 (365)	67 (460)	29–70	—
		Over 0.029 (0.737)			—	38–68
		Over 0.020 (0.508) to 0.039 (0.991) incl			20–66	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	27–62

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TABLE 4.44 Tensile Strength Requirements and Approximate Rockwell Hardness Values (*Continued*)

Temper designation†			Tensile strength, ksi* (MPa)		Approximate Rockwell hardness	
Standard	Former	Thickness, in (mm)	Min	Max	B scale	Superficial 30-T
		Copper Alloy UNS No. C52100 (*Continued*)				
H02	Half hard	Over 0.039 (0.991)	69 (475)	84 (580)	76–91	—
		Over 0.029 (0.737)			—	67–78
		Over 0.020 (0.508) to 0.039 (0.991) incl			69–88	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	63–75
H04	Hard	Over 0.039 (0.991)	85 (585)	100 (690)	91–97	—
		Over 0.029 (0.737)			—	76–81
		Over 0.020 (0.508) to 0.039 (0.991) incl			89–95	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	73–80
H06	Extra hard	Over 0.039 (0.991)	97 (670)	112 (770)	95–100	—
		Over 0.029 (0.737)			—	78–83
		Over 0.020 (0.508) to 0.039 (0.991) incl			93–98	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	77–82
H08	Spring	Over 0.039 (0.991)	105 (720)	119 (820)	97–102	—
		Over 0.029 (0.737)			—	79–84
		Over 0.020 (0.508) to 0.039 (0.991) incl			95–100	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	78–83
H10	Extra spring	Over 0.039 (0.991)	110 (760)	122 (830)	98–103	—
		Over 0.029 (0.737)			—	80–84
		Over 0.020 (0.508) to 0.039 (0.991) incl			96–101	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	79–83
		Copper Alloy UNS No. C52400				
M20	As hot rolled	Over 0.188 (4.775)	55 (380)	75 (515)	—	—
O60	Soft	Over 0.039 (0.991)	58 (400)	73 (505)	35–75	—
		Over 0.029 (0.737)			—	40–78

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		Over 0.029 (0.737)			—	40–78
		Over 0.020 (0.508) to 0.039 (0.991) incl			25–71	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	29–84
H02	Half hard	Over 0.039 (0.991)	76 (525)	91 (625)	78–95	—
		Over 0.029 (0.737)			—	67–80
		Over 0.020 (0.508) to 0.039 (0.991) incl			74–93	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	63–77
H04	Hard	Over 0.039 (0.991)	94 (650)	109 (750)	94–101	—
		Over 0.029 (0.737)			—	78–82
		Over 0.020 (0.508) to 0.039 (0.991) incl			92–100	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	75–81
H06	Extra hard	Over 0.039 (0.991)	107 (740)	122 (830)	98–103	—
		Over 0.029 (0.737)			—	80–84
		Over 0.020 (0.508) to 0.039 (0.991) incl			97–102	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	79–83
H08	Spring	Over 0.039 (0.991)	115 (790)	129 (890)	99–104	—
		Over 0.029 (0.737)			—	81–85
		Over 0.020 (0.508) to 0.039 (0.991) incl			98–103	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	80–84
H10	Extra spring	Over 0.039 (0.991)	120 (830)	133 (920)	100–105	—
		Over 0.029 (0.737)			—	82–86
		Over 0.020 (0.508) to 0.039 (0.991) incl			99–104	—
		Over 0.010 (0.254) to 0.029 (0.737) incl			—	81–85

NOTE: Plate is generally available in only the "As hot-rolled" (M20) temper. Required properties for other tempers shall be agreed upon between the manufacturer and the purchaser at the time of placing the order.

* ksi = 1000 psi.

† Standard designations defined in Practice B 601.

‡ Editorially corrected.

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TABLE 4.45 Mechanical Property Requirements for Material in the Solution Heat-Treated or Solution Heat-Treated and Cold-Worked Condition

Temper designation[§]		Tensile strength, ksi* (MPa)	Elongation[†] in 2 in or 50 mm, min, %	Rockwell hardness[‡]		
Standard	Former			B scale	30T scale	15T scale
TB00	A	60–78 (410–540)	35	45–78	46–67	75–85
TD01	¼ H	75–88 (520–610)	10	68–90	62–75	83–89
TD02	½ H	85–100 (590–690)	5	88–96	74–79	88–91
TD04	H	100–120 (690–830)	2	96–102	79–83	91–94

* ksi = 1000 psi.

[†] Elongation requirement applies only to strip 0.004 in (0.102 mm) and thicker.

[‡] The thickness of material that may be tested by use of the Rockwell hardness scales is as follows:

B scale	0.040 in (1.016 mm) and over
30T scale	0.020 to 0.040 in (0.508 to 1.016 mm), excl.
15T scale	0.015 to 0.020 in (0.381 to 0.508 mm), excl.

Hardness values shown apply only to direct determinations, not converted values.

[§] Standard designations defined in Practice B 601.

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TABLE 4.46 Mechanical Property Requirements After Precipitation Heat Treatment*

Temper designation		Tensile strength, ksi† (MPa)	Yield strength, ksi (MPa), min, 0.2% offset	Elongation in 2 in (50 mm), min, %‡	Rockwell hardness§, min		
Standard	Former				C scale	30N scale	15N scale
			Copper Alloy UNS No. C17000				
TF00	AT	150–180¶ (1030–1240)	130 (890)	3	33	53	76.5
TH01	¼ HT	160–190¶ (1100–1310)	135 (930)	2.5	35	55	77
TH02	½ HT	170–200¶ (1170–1380)	145 (1000)	1	37	57	78.5
TH04	HT	180–210¶ (1240–1450)	155 (1070)	1	38	58	79.5
			Copper Alloy UNS No. C17200				
TF00	AT	165–195¶ (1140–1340)	140 (960)	3	36	56	78
TH01	¼ HT	175–205¶ (1210–1410)	150 (1030)	2.5	36	56	79
TH02	½ HT	185–215¶ (1280–1480)	160 (1130)	1	38	58	79.5
TH04	HT	190–220¶ (1310–1520)	165 (1140)	1	38	58	80

* These values apply to mill products (Section 11). See 11.3 for exceptions in end products.

† ksi = 1000 psi.

‡ Applicable to material 0.004 in (0.102 mm) and thicker.

§ The thickness of material that may be tested by use of the Rockwell hardness scales is as follows:

C scale	0.040 in (1.016 mm) and over
30N scale	0.020 to 0.040 in (0.508 to 1.016 mm), excl.
15N scale	0.015 to 0.02 in (0.381 to 0.508 mm), excl.

Hardness values shown apply only to direct determinations, not converted values.

¶ The upper limits in the tensile strength column are for design guidance only.

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TABLE 4.47 Mechanical Property Requirements—Mill-Hardened Condition*

Temper designation		Tensile strength, ksi† (MPa)	Yield strength, ksi (MPa), 0.2% offset	Elongation in 2 in (50 mm), min, %‡	Rockwell hardness,§ min		
Standard	Former†				C scale	30N scale	15N scale
			Copper Alloy UNS No. C17000				
TM00	AM	100–110¶ (690–760)	70–95 (480–660)	18	18	37	67.5
TM01	¼ HM	110–120¶ (760–830)	80–110 (550–760)	15	20	42	70
TM02	½ HM	120–135¶ (830–930)	95–125 (660–860)	12	24	45	72
TM04	HM	135–150¶ (930–1040)	110–135 (760–930)	9	28	48	75
TM05	SHM	150–160¶ (1030–1100)	125–140 (860–970)	9	31	52	75.5
TM06	XHM	155–175¶ (1070–1210)	135–165 (930–1140)	3	32	52	76
			Copper Alloy UNS No. C17200				
TM00	AM	100–110¶ (690–760)	70–95 (480–660)	16	R_B95	37	67.5
TM01	¼ HM	110–120¶ (760–830)	80–110 (550–760)	15	20	42	70
TM02	½ HM	120–135¶ (830–930)	95–125 (660–860)	12	23	44	72
TM04	HM	135–150¶ (930–1030)	110–135 (760–930)	9	28	48	75

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TM05	SHM	150–160[¶] (1030–1100)	125–140 (860–970)	9	31	52	75.5
TM06	XHM	155–175[¶] (1070–1210)	135–170 (930–1170)	4	32	52	76
TM08	XHMS	175–190[¶] (1210–1310)	150–180 (1030–1240)	3	33	53	76.5

* These values apply to mill products (Section 11). See 11.3 for exceptions in end products.

† ksi = 1000 psi.

‡ Applicable to material 0.004 in (0.102 mm) and thicker.

§ The thickness of material that may be tested by use of the Rockwell hardness scales is as follows:

C scale	0.040 in (1.016 mm) and over
30N scale	0.020 to 0.040 in (0.508 to 1.016 mm), excl.
15N scale	0.015 to 0.020 in (0.381 to 0.508 mm), excl.

Hardness values shown apply only to direct determinations, not converted values.

¶ The upper limits in the tensile strength column are for design guidance only.

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TABLE 4.48 Classification of Coppers

Designations	Type of copper	UNS nos.[a]	Form in which copper is available[b]							
			From refiners				From fabricators			
			Wire bars	Billets	Cakes	Ingots and ingot bars	Flat products	Pipe and tube	Rod and wire	Shapes
CATH	Electrolytic cathode		Cathodes only							
		Tough-Pitch Coppers								
ETP	Electrolytic tough pitch	C11000	x	x	x	x	x	x	x	x
RHC	Remelted, high-conductivity tough pitch	C11010	x	x	x	x	x	x	x	x
ETP	Electrolytic tough pitch (anneal resist)	C11100	x	x	x		x	x	x	x
CRTP	Chemically refined tough pitch	C11030	x	x	x	x	x	x	x	x
FRHC	Fire-refined, high-conductivity tough pitch	C11020	x	x	x	x	x	x	x	x
ETP[c]	Silver-bearing, tough pitch	C11300, C11400, C11500, C11600	x	x	x	x	x	x	x	x
FRTP	Fire-refined, tough pitch	C12500		x	x	x	x	x	x	x
FRSTP	Fire-refined tough pitch with silver	C12700, C12800, C12900, C1300		x	x	x	x			x
		Oxygen-Free Coppers (Without Use of Deoxidants)								
OFE	Oxygen-free, electronic	C10100	x	x	x		x	x	x	x
OF	Oxygen-free	C10200	x	x	x		x	x	x	x
OFS	Oxygen-free, silver-bearing	C10400, C10500, C10700	x	x	x		x	x	x	x
OFXLP	Oxygen-free, extra low phosphorus	C10300	x	x	x		x	x	x	x
OFLP	Oxygen-free, low phosphorus	C10800	x	x	x		x	x	x	x

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		Deoxidized Coppers						
DLP	Phosphorized, low-residual phosphorus	C12000	x	x	x	x	x	x
DLPS[d]	Phosphorized, low-residual phosphorus silver-bearing	C12100	x	x	x	x	x	x
DHP[e]	Phosphorized, high-residual phosphorus	C12200	x	x	x	x	x	x
DHPS[d]	Phosphorized, high-residual phosphorus silver-bearing	C12300	x	x	x	x	x	x
DPA	Phosphorized, arsenic-bearing	C14200	x		x	x		
DPTE[f]	Phosphorized, tellurium-bearing	C14500	x				x	
		Other Coppers						
	Sulfur-bearing	C14700	x				x	
	Zirconium-bearing	C15000	x	x	x		x	
PTE	Tellurium-bearing	C14500	x				x	

[a] The chemical compositions associated with these numbers are listed in the product specifications and in the Standard Designations for Copper and Copper Alloys.
[b] The x in the table indicates commercial availability.
[c] This includes types ETP, CRTP, and FRHC coppers to which silver has been added in amounts agreed upon.
[d] This includes oxygen-free copper to which phosphorus and silver have been added in amounts agreed upon.
[e] This includes oxygen-free copper to which phosphorus has been added.
[f] This includes oxygen-free tellurium-bearing copper to which phosphorus has been added in amounts agreed upon.
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TABLE 4.49 Specifications of Magnesium Wrought Alloys

Alloy designation			Form	ASTM	AMS	Military or federal
UNS	ASTM and SAE	Old SAE				
M11311	AZ31B	510	Sheet and plate	B90	4375, 4376, 4377	QQ-M-44
			Bar, rod, shapes	B107	—	QQ-M-31
			Tube	B107	—	WW-T-825
			Forgings	B91	—	QQ-M-40
M11610	AZ61A	520	Bar, rod, shapes	B107	4350	QQ-M-31
			Tube	B107	4350	WW-T-825
			Wire (welding rod)	—	—	Mil-R-6944
			Forgings	B91	4358*	QQ-M-40
M11800	AZ80A	523	Bar, rod, shapes	B107	—	QQ-M-31
			Forgings	B91	4360*	QQ-M-40
M14141	LA141A		Sheet and plate	B90	—	—
M13310	HK31A	507	Sheet and plate	B90	4384, 4385	Mil-M-26075
M13210	HM21A		Sheet and plate	B90	4383, 4390	Mil-M-8917
			Forgings	—	4363	QQ-M-40
M13312	HM31A		Bar, rod, shapes	—	4388, 4389	Mil-M-8916
M15100	M1A	522	Bar, rod, shapes	B107	—	QQ-M-31
			Forgings	—	—	QQ-M-40
M16100	ZE10A	534	Sheet and plate	B90	—	Mil-M-46037
M16400	ZK40A		Bar, rod, shapes	B107	—	—
M16600	ZK60A	524	Bar, rod, shapes	B107	4352	QQ-M-31
			Tube	B107	4352	WW-T-825
			Forgings	B91	4362	QQ-M-40

* Noncurrent specifications.

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TABLE 4.50 Physical Properties and Characteristics of Magnesium Sand-Casting Alloys

Alloy designation			Approximate melting range, °F (°C)				Foundry characteristics[c]					Other characteristics				
UNS	ASTM and SAE	Old SAE	Nonequilibrium solidus[a]	Solidus	Liquidus	Pattern shrinkage allowance, in/ft (mm/m)[b]	Pressure tightness	Fluidity[d]	Microporosity tendency[e]	Normally heat treated	Castability	Machining[f]	Electroplating[g]	Surface treatment[h]	Suitability to brazing[i]	Suitability to welding
M10100[m]	AM100A	502	810 (432)	867 (464)	1100 (593)	5/32 (13.0)	2	1	2	Yes	2	1	2	2	No	1
M11630	AZ63A	50	685 (363)	850 (454)	1130 (610)	5/32 (13.0)	3	1	3	Yes	3	1	1	1	No	3
M11810[m]	AZ81A	505	790 (421)	882 (472)	1115 (602)	5/32 (13.0)	2	1	2	Yes	1	1	2	2	No	1
M11914[m]	AZ91C	504	785 (418)	875 (468)	1105 (596)	5/32 (13.0)	2	1	2	Yes	1	1	2	2	No	2
M11920[m]	AZ92A	500	770 (410)	830 (443)	1100 (593)	5/32 (13.0)	2	1	2	Yes	2	1	2	2	No	2
M12330[n]	EZ33A	506	— —	1010 (543)	1189 (643)	3/16 (15.5)	1	2	1	Yes	1	1	1	1	No	1
M13310[m]	HK31A	507	— —	1092 (589)	1204 (651)	7/32 (18.0)	1	2	1	Yes	1	1	1	1	—[k]	1
M13320[n]	HZ32A	—	— —	1026 (552)	1198 (648)	3/16 (15.5)	1	2	1	Yes	1	1	—[k]	2	—[k]	2
M18010[p]	K1A	—	— —	— —	1205 (652)	3/16 (15.5)	2	2	2	No	2	1	3	2	—[k]	1
M18210	QH21A	—	— —	1004 (539)	1184 (640)	3/16 (15.5)	2	2	2	Yes	1	1	2	1	No	—[k]
M18220[m]	QE22A	—	— —	1020 (549)	1190 (643)	5/32 (13.0)	2	2	2	Yes	1	1	2	1	—[k]	1
M16410[p]	ZE41A	—	— —	950 (510)	1184 (640)	3/16 (15.5)	—[k]	2	—[k]	Yes	1	1	1	1	No	2
M16630[p]	ZE63A	—	— —	510 (266)	950 (510)	3/16 (15.5)	1	2	1	Yes	1	1	—[k]	1	No	1
M16620	ZH62A	508	— —	— —	1169 (632)	5/32 (13.0)	2	2	2	Yes	2	1	1	1	No	—[k]
M16510	ZK51A	509	— —	1020 (549)	1185 (641)	5/32 (13.0)	3	2	3	Yes	3	1	2	2	No	3
M16610	ZK61A	513	— —	985 (529)	1175 (635)	5/32 (13.0)	3	2	3	Yes	3	1	2	1	No	3

[a] As measured on metal solidified under normal casting conditions.

[b] Allowance for average castings. Shrinkage requirements will vary with intricacy of design and dimensions. (1 in/ft × 8.333 = % shrinkage.)

[c] Rating of 1 indicates best of group; 3 indicates poorest of group.

[d] Ability of liquid alloy to flow readily in mold and fill thin sections.

[e] Based on radiographic evidence.

[f] Composite rating based on ease of cutting, chip characteristics, quality of finish, and tool life. Ratings, in the case of heat-treatable alloys, based on –T6 type temper. Other tempers, particularly the annealed temper, may have lower ratings.

[g] Ability of casting to take and hold an electroplate applied by present standard methods.

[h] Ability of castings to be cleaned in standard pickle solutions and to be conditioned for best paint adhesion.

[i] Refers to suitability of alloy to withstand brazing temperature without excessive distortion or melting.

[j] Based on ability of material to be fusion welded with filler rod of same alloy.

[k] Inexperience with these alloys under wide production conditions makes it undesirable to supply ratings at this time.

[m] Properties applicable for permanent mold and investment castings.

[n] Properties applicable for permanent mold castings also.

[p] Properties applicable for investment castings also.

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TABLE 4.51 Tensile Requirements

Alloy				Specified diameter or thickness, in[a,c]	Specified cross-sectional area, in^2 or OD of tube, in	Tensile strength, min		Yield strength (0.2% offset), min		Elongation in 2 in or 4 × dia., min, %
UNS no.	ASTM no.	Temper	Form			ksi	(MPa)[d]	ksi	(MPa)[d]	
M11311	AZ31B	F	Bars, rods, shapes, and wire	0.249 and under	All	35.0	(241)	21.0	(145)	7
				0.250–1.499	All	35.0	(241)	22.0	(152)	7
				1.500–2.499	All	34.0	(234)	22.0	(152)	7
				2.500–4.999	All	32.0	(221)	20.0	(138)	7
			Hollow shapes	All	All	32.0	(221)	16.0	(110)	8
			Tubes	0.028–0.500	6.000 and under	32.0	(221)	16.0	(110)	8
				0.251–0.750		32.0	(221)	16.0	(110)	4
M11610	AZ61A	F	Bars, rods, shapes, and wire	0.249 and under	All	38.0	(262)	21.0	(145)	8
				0.250–2.499	All	39.0	(269)	24.0	(165)	9
				2.500–4.999	All	40.0	(276)	22.0	(152)	7
			Hollow shapes	All	All	36.0	(248)	16.0	(110)	7
			Tubes	0.028–0.750	6.000 and under	36.0	(248)	16.0	(110)	7
M11800	AZ80A	F	Bars, rods, shapes, and wire	0.249 and under	All	43.0	(296)	28.0	(193)	9
				0.250–1.499	All	43.0	(296)	28.0	(193)	8
				1.500–2.499	All	43.0	(296)	28.0	(193)	6
				2.500–4.999	All	42.0	(290)	27.0	(186)	4
M11800	AZ80A	T5	Bars, rods, shapes, and wire	0.249 and under	All	47.0	(324)	30.0	(207)	4
				0.250–2.499	All	48.0	(331)	33.0	(228)	4
				2.500–4.999	All	45.0	(310)	30.0	(207)	2
M15100	M1A	F	Bars, rods, shapes, and wire	0.249 and under	All	30.0	(207)	[b]	—	2
				0.250–1.499	All	32.0	(221)	[b]	—	3
				1.500–2.499	All	32.0	(221)	[b]	—	2

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				2.500–4.999	All	29.0	(200)	[b]	—	2
			Hollow shapes	All	All	28.0	(193)	[b]	—	2
			Tubes	0.028–0.750	6.000 and under	28.0	(193)	[b]	—	2
M16400	ZK40A	T5	Bars, rods, shapes, and wire	All	4.999 and under	40.0	(276)	37.0	(255)	4.0
			Hollow shapes	All	All	40.0	(276)	37.0	(255)	4.0
			Tubes	0.062–0.500	3.000 and under	40.0	(276)	36.0	(248)	4.0
M16600	ZK60A	F	Bars, rods, shapes, and wire	All	4.999 and under	43.0	(296)	31.0	(214)	5
					5.000–39.999	43.0	(296)	31.0	(214)	4
			Hollow shapes	All	All	40.0	(276)	28.0	(193)	5
			Tubes	0.028–0.750	3.000 and under	40.0	(276)	28.0	(193)	5
M16600	ZK60A	T5	Bars, rods, shapes, and wire	All	4.999 and under	45.0	(310)	36.0	(248)	4
			Hollow shapes	All	All	46.0	(317)	38.0	(262)	4
			Tubes	0.028–0.250	3.000 and under	46.0	(317)	38.0	(262)	4
				0.094–1.188	3.001–8.500	44.0	(303)	33.0	(228)	4

NOTE: For purposes of determining conformance with this specification, each value for tensile strength and yield strength shall be rounded to the nearest 100 psi and each value for elongation shall be rounded to the nearest 0.5%, both in accordance with the rounding method of Recommended Practice E 29.

[a] Intermediate dimensions shall be rounded off to the third decimal place in accordance with Recommended Practice E 29.

[b] Not required.

[c] Wall thickness of tubes.

[d] The values in megapascals are included for information only.

[e] Elongation of full-section and machined sheet-type specimens is measured in 2 in; of machined round specimens, in 4 × specimen dia.

[f] For material of such dimensions that a standard test specimen cannot be obtained, for wire less than 0.125 in diameter, or for material thinner than 0.062 in the test for elongation is not required.

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tetrachloride with magnesium. Titanium is a lustrous, white metal with low density and good strength. The specific gravity of titanium is 4.54 g/cm^3, with a weight of 0.164 lb/in^3. The pure metal burns in air and is the only element that burns in nitrogen gas.

Titanium is used extensively in modern aircraft and aerospace vehicles, where a lightweight alloy with high strength finds many applications. Titanium is the ninth most abundant element in the earth's crust.

Table 4.52 lists the tensile and bend requirements of titanium alloys for annealed titanium plate, sheet, and strip, which are classified as follows:

Grades 1 through 4: Unalloyed titanium

Grade 5: Titanium alloy (6 percent aluminum, 4 percent vanadium)

Grade 6: Titanium alloy (5 percent aluminum, 2.5 percent tin)

Grade 7: Unalloyed titanium plus palladium

Grade 9: Titanium alloy (3 percent aluminum, 2.5 percent vanadium)

Grade 11: Unalloyed titanium plus palladium

Grade 12: Titanium alloy (0.3 percent molybdenum, 0.8 percent nickel)

Table 4.53 lists the mechanical properties of wrought titanium alloys.

4.6 The Unified Numbering System (UNS) for Metals and Alloys

The Unified Numbering System (UNS) provides a means of coordinating many nationally used numbering systems currently administered by societies, trade associations, and the producers of metals and alloys, thereby avoiding confusion caused by use of more than one identification number for the same material or by having the same number assigned to two or more entirely different materials. Table 4.54 shows the primary series of numbers, and Table 4.55 lists the secondary division of some series of numbers. When you know the UNS number for a metal or alloy, you may use these

(Text continued on page 248.)

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TABLE 4.52 Tensile and Bend Requirements of Titanium Alloys

Grade	Tensile strength,* min		Yield strength,* 0.2% offset				Elongation in 2 in or 50 mm, min, %	Bend test†	
			min		max			Under 0.070 in (1.8 mm) in thickness	0.070 to 0.187 in (1.8 to 4.75 mm) in thickness
	ksi	MPa	ksi	MPa	ksi	MPa			
1	35	240	25	170	45	310	24	3*T*	4*T*
2	50	345	40	275	65	450	20	4*T*	5*T*
3	65	450	55	380	80	550	18	4*T*	5*T*
4	80	550	70	485	95	655	15	5*T*	6*T*
5	130	895	120	830	—	—	10‡,§	9*T*	10*T*
6	120	830	115	795	—	—	10‡	8*T*	9*T*
7	50	345	40	275	65	450	20	4*T*	5*T*
9	90	620	70	485	—	—	15¶	5*T*	6*T*
11	35	240	25	170	45	310	24	3*T*	4*T*
12	70	483	50	345	—	—	18	4*T*	5*T*

* Minimum and maximum limits apply to tests taken both longitudinal and transverse to the direction of rolling. Mechanical properties for conditions other than annealed or plate thickness over 1 in (25 mm) may be established by agreement between the manufacturer and the purchaser.

† *T* equals the thickness of the bend test specimen. Bend tests are not applicable to material over 0.187 in (4.75 mm) in thickness.

‡ For grades 5 and 6 the elongation on materials under 0.025 in (0.635 mm) in thickness may be obtained only by negotiation.

§ For grade 5, the elongation will be 8% minimum for thicknesses between 0.025 and 0.063 in.

¶ Elongation for continuous rolled and annealed (strip product from coil) for grade 9 shall be 12% minimum in the longitudinal direction and 8% minimum in the transverse direction.

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TABLE 4.53 Mechanical Properties of Wrought Titanium Alloys

Nominal composition (%)	Condition	Tensile strength (ksi)	Room temperature		Reduction in area (%)
			Yield strength (ksi)	Elongation (%)	
Commercially Pure					
99.5 Ti	Annealed	48	35	30	55
99.2 Ti	Annealed	63	50	28	50
99.1 Ti	Annealed	75	65	25	45
99.0 Ti	Annealed	96	85	20	40
99.2 Ti[a]	Annealed	63	50	28	50
98.9[b]	Annealed	75	65	25	42
Alpha Alloys					
5 Al, 2.5 Sn	Annealed	125	117	16	40
5 Al, 2.5 Sn (low O_2)	Annealed	117	108	16	—
Near Alpha Alloys					
8 Al, 1 Mo, 1 V	Duplex annealed	145	138	15	28
11 Sn, 1 Mo, 2.25 Al, 5.0 Zr, 1 Mo, 0.2 Si	Duplex annealed	160	144	15	35
6 Al, 2 Sn, 4 Zr, 2 Mo	Duplex annealed	142	130	15	35
5 Al, 5 Sn, 2 Zr, 2 Mo, 0.25 Si	975°C (1785°F) (½ h), AC + 595°C (1100°F) (2 h), AC	152	140	13	—
6 Al, 2 Nb, 1 Ta, 1 Mo	As-rolled 2.5-cm (1-in) plate	124	110	13	34
6 Al, 2 Sn, 1.5 Zr, 1 Mo, 0.35 Bi, 0.1 Si	Beta forge + duplex anneal	147	137	11	—
Alpha-Beta Alloys					
8 Mn	Annealed	137	125	15	32
3 Al, 2.5 V	Annealed	100	85	20	—
6 Al, 4 V	Annealed	144	134	14	30
	Solution + age	170	160	10	25
6 Al, 4 V (low O_2)	Annealed	130	120	15	35
6 Al, 6 V, 2 Sn	Annealed	155	145	14	30
	Solution + age	185	170	10	20
7 Al, 4 Mo	Solution + age	160	150	16	22
6 Al, 2 Sn, 4 Zr, 6 Mo	Solution + age	184	170	10	23
6 Al, 2 Sn, 2 Zr, 2 Mo, 2 Cr, 0.25 Si	Solution + age	185	165	11	33
10 V, 2 Fe, 3 Al	Solution + age	185	174	10	19
Beta Alloys					
13 V, 11 Cr, 3 Al	Solution + age	177	170	8	—
	Solution + age	185	175	8	—
8 Mo, 8 V, 2 Fe, 3 Al	Solution + age	190	180	8	—
3 Al, 8 V, 6 Cr, 4 Mo, 4 Zr	Solution + age	210	200	7	—
	Annealed	128	121	15	—
11.5 Mo, 6 Zr, 4.5 Sn	Solution + age	201	191	11	—

[a] Also contains 0.2 Pd.
[b] Also contains 0.8 Ni and 0.3 Mo.
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TABLE 4.54 Primary Series of Numbers

	Nonferrous Metals and Alloys
A00001–A99999	Aluminum and aluminum alloys
C00001–C99999	Copper and copper alloys
E00001–E99999	Rare earth and rare earth-like metals and alloys
L00001–L99999	Low-melting metals and alloys
M00001–M99999	Miscellaneous nonferrous metals and alloys
N00001–N99999	Nickel and nickel alloys
P00001–P99999	Precious metals and alloys
R00001–R99999	Reactive and refractory metals and alloys
Z00001–Z99999	Zinc and zinc alloys
	Ferrous Metals and Alloys
D00001–D99999	Specified mechanical properties steels
F00001–F99999	Cast irons and cast steels
G00001–G99999	AISI and SAE carbon and alloy steels
H00001–H99999	AISI H-steels
J00001–J99999	Cast steels (except tool steels)
K00001–K99999	Miscellaneous steels and ferrous alloys
S00001–S99999	Heat and corrosion resistant (stainless) steels
T00001–T99999	Tool steels
	Specialized Metals and Alloys
W00001–W99999	Welding filler metals, covered and tubular electrodes, classified by weld deposit composition

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TABLE 4.55 Secondary Division of Some Series of Numbers

E00001–E99999 Rare Earth and Rare Earth–Like Metals and Alloys	
E00000–E00999	Actinium
E01000–E20999	Cerium
E21000–E45999	Mixed rare earths*
E46000–E47999	Dysprosium
E48000–E49999	Erbium
E50000–E51999	Europium
E52000–E55999	Gadolinium
E56000–E57999	Nolmium
E58000–E67999	Lanthanum
E68000–E68999	Lutetium
E69000–E73999	Neodymium
E74000–E77999	Praseodymium
E78000–E78999	Promethium
E79000–E82999	Samarium
E83000–E84999	Scandium
E85000–E86999	Terbium
E87000–E87999	Thulium
E88000–E89999	Ytterbium
E90000–E99999	Yttrium
F00001–F9999 Cast Irons K00001–K99999 Miscellanenous Steels and Ferrous Alloys L00001–L99999 Low-Melting Metals and Alloys	
L00001–L00999	Bismuth
L01001–L01999	Cadmium
L02001–L02999	Cesium
L03001–L03999	Gallium
L04001–L04999	Indium
L05001–L05999	Lead
L06001–L06999	Lithium
L07001–L07999	Mercury
L08001–L08999	Potassium
L09001–L09999	Tubidium
L10001–L10999	Selenium
L11001–L11999	Sodium
L12001–L12999	Thallium
L13001–L13999	Tin
M00001–M99999 Miscellaneous Nonferrous Metals and Alloys	
M00001–M00999	Antimony
M01001–M01999	Arsenic
M02001–M02999	Barium
M03001–M03999	Calcium
M04001–M04999	Germanium
M05001–M05999	Plutonium
M06001–M06999	Strontium

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M07001–M07999	Tellurium
M08001–M08999	Uranium
M10001–M19999	Magnesium
M20001–M29999	Manganese
M30001–M39999	Silicon
P00001–P99999 Precious Metals and Alloys	
P00001–P00999	Gold
P01001–P01999	Iridium
P02001–P02999	Osmium
P03001–P03999	Palladium
P04001–P04999	Platinum
P05001–P05999	Rhodium
P06001–P06999	Ruthenium
P07001–P07999	Silver
R00001–R99999 Reactive and Refractory Metals and Alloys	
R01001–R01999	Boron
R02001–R02999	Hafnium
R03001–R03999	Molybdenum
R04001–R04999	Niubium (columbium)
R05001–R05999	Tantalum
R06001–R06999	Thorium
R07001–R07999	Tungsten
R08001–R08999	Vanadium
R10001–R19999	Beryllium
R20001–R29999	Chromium
R30001–R39999	Cobalt
R40001–R49999	Rhenium
R50001–R59999	Titanium
R60001–R69999	Zirconium
W00001–W99999 Welding Filler Metals Classified by Weld Deposit Composition	
W00001–W09999	Carbon steel with no significant alloying elements
W10000–W19999	Manganese-molybdenum low-alloy steels
W20000–W29999	Nickel low-alloy steels
W30000–W39999	Austenitic stainless steels
W40000–W49999	Ferritic stainless steels
W50000–W59999	Chromium low-alloy steels
W60000–W69999	Copper-base alloys
W70000–W79999	Surfacing alloys
W80000–W89999	Nickel-base alloys
Z00001–Z99999 Zinc and Zinc Alloys	

* Alloys in which the rare earths are used in the ratio of their natural occurrence (that is, unseparated rare earths). In this mixture, cerium is the most abundant of the rare earth elements.

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tables to determine the prime material (metal) or classification of alloy represented by the UNS number.

4.7 Hardness Tests and Hardness Number Conversions

4.7.1 Brinell hardness numbers (HB)

The Brinell hardness system is one of the most widely used systems for indicating the hardness of metals and alloys. The Brinell hardness number of a material may be calculated from the following equation:

$$\text{HB} = \frac{P}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

where HB = Brinell hardness number
P = load applied to the test ball, kg
D = diameter of ball, mm
d = measured diameter at the rim of the impression in the material, mm

The standard ball is 10 mm in diameter, and standard loads are 500, 1500, and 3000 kg. The test is not valid when the hardness of the test material is above the anticipated Brinell hardness number of 630.

4.7.2 Vickers hardness numbers (HV)

The Vickers hardness is determined by forcing a square-base diamond pyramid having an apex angle of 136° into the test specimen under a load ranging from 3 to 50 kg and then measuring the diagonals of the indentation created. The Vickers hardness is defined as the load per unit area of surface contact in kilograms per square millimeter and may be calculated from the average diagonal using the following equation:

$$\text{HV} = \frac{2L \sin \frac{\alpha}{2}}{d^2}$$

where HV = Vickers hardness number
d = length of average diagonal, mm
α = apex angle, 136°
L = load, kg

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4.8 Plastics (Thermoplastics and Thermoset Plastics)

Plastic materials are derived mainly from petroleum products. The types, trade names, and compositions of the various modern plastics form a long list, with more being developed as required to meet specific design and application needs in industry.

A *thermoplastic* is a plastic in which the finished molded part may be remelted for remolding. A *thermoset plastic* is a plastic in which the chemical reaction cannot be reversed, thus allowing the part to be cast only once. Thermoplastics are extruded, injection-molded, and cast in dies. Thermoset plastics usually are compression-molded. Some of the thermoplastics are also formulated for thermoset applications, such as the urethanes. Table 4.56 lists the common trade names, suppliers, SAE symbols, and plastic "family" names for most plastics.

Common plastics and compositions. Listed here are some of the more prevalent plastics and compositions.

ABS (acrylonitrile-butadiene-styrene)

Acetal (Delrin, Celcon)

Acetate (cellulose)

Acrylic (Lucite, Plexiglas)

Benelex

Epoxy, epoxy glass

Diallyl phthalate, Melamine

Mylar (polyester film)

Nylon

Phenol formaldehyde

Phenolic laminates

Polycarbonate (Lexan)

Polyester glass

Polyethylene

Polypropylene

(Text continued on page 263.)

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TABLE 4.56 Common Plastics

Common/trade name	Supplier	SAE symbol	Plastic "family" name
ABS	Generic Name	ABS	Acrylonitrile/butadiene/styrene
Absafil	Wilson Fiberfil International	ABS	Acrylonitrile/butadiene/styrene
Acetal	Generic Name	POM	Polyoxymethylene: polyformaldehyde
Aclar	Ausimont	PCTFE	Polychlorotrifluoroethylene
Acrylic	Generic Name	PMMA	Poly (methyl methacrylate)
Acrylite	Cyro Industries	PMMA	Poly (methyl methacrylate)—"acrylic"
Adiprane	Uniroyal Inc.	PUR	Polyurethane, thermoset (unsaturated)
Alathon	E.I. Dupont de Nemours & Co.	PE	Polyethylene
Alton	International Polymers	PPS + PTFE	Polyphenylene sulfide + polytetrafluoroethylene
Ampol	American Polymers Inc.	CA	Cellulose acetate
Andrez	Unknown	SB	Styrene-butadiene
Apex	Teknor Apex Co.	PVC	Poly (vinyl chloride)
Araldrite	Ciba-Geigy Corp.	EP	Epoxide: epoxy
Aramid	Generic Name	PARA	Polyarylamid (polyaramide)
Ardel	Union Carbide Corp.	PAT	Polyester, thermoplastic—"polyarylate"
Arloy	Arco Chemical Co.	PC + SMA	Polycarbonate + styrene maleic anhydride
Arylon	E.I. Dupont de Nemours & Co.	PAT	Polyester, thermoplastic—"polyarylate"
Astrel	Amoco Chemicals Corp.	PASU	Polyarylsulfone
Azdel	Azdel Inc.	PP	Polypropylene
Bakelite	Union Carbide Corp.	PF	Phenol-formaldehyde
Bayblend	Mobay Chemical Corp.	ABS + PC	Acrylonitrile/butadiene/styrene + polycarbonate
Bayflex	Mobay Chemical Corp.	PUR	Polyurethane, thermoset
Bayflex	Mobay Chemical Corp.	TPU	Thermoplastic elastomer
Bexloy C	E.I. Dupont de Nemours & Co.	PA+	Polyamide (amorphous) blend
Bexloy K & J	E.I. Dupont de Nemours & Co.	PBT + PET	Polybutylene terephthalate + polyethylene terephthalate

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BMC	Generic Name	UP	Polyester, thermoset (unsaturated)
Butvar	Monsanto Co.	PVB	Poly (vinyl butyral)
Cadon	Monsanto Co.	ABS	Acrylonitrile/butadiene/styrene
Cadon	Monsanto Co.	ABS + SMA	Acrylonitrile/butadiene/styrene + styrene maleic anhydride
Cadon	Monsanto Co.	SMA	Styrene maleic anhydride
Calibre	Dow Chemical Co.	PC	Polycarbonate
Capron	Allied Engineered Plastics	PA	Polyamide—"nylon"
Castethane	Dow Chemical Co.	PUR	Polyurethane, thermoset
Celanese	Celanese Engineering Resins	PA	Polyamide—"nylon"
Celanese N	Celanese Engineering Resins	PA + RUBBER	Polyamide + rubber
Celanex	Celanese Engineering Resins	PBT	Polyester, thermoplastic—"polybutylene terephthalate"
Celanex	Celanese Engineering Resins	PBT + PET	Polybuthylene terephthalate + polyethylene terephthalate
Celanex	Celanese Engineering Resins	PBT + RUBBER	Polybutylene terephthalate + rubber
Celcon	Celanese Engineering Resins	POM	Polyoxymethylene: polyformaldehyde—"acetal"
Celcon C	Celanese Engineering Resins	POM + RUBBER	Polyoxymethylene + rubber
Cellidor	Bayer AG	CA	Cellulose acetate
Cellidor	Bayer AG	CAP	Cellulose acetate propionate
Cellidor	Bayer AG	CP	Cellulose propionate
Centrex	Monsanto Co.	ASA	Acrylonitrile/styrene/acrylate
Corvel	Polymer Corp.	EP	Epoxide
Cyanaprene	American Cyanamid Co.	PUR	Polyurethane, thermoset (unsaturated)
Cycolac	Borg-Warner Chemicals Inc.	ABS	Acrylonitrile/butadiene/styrene
Cycoloy	Borg-Warner Chemicals Inc.	ABS + TPU	Acrylonitrile/butadiene/styrene + thermoplastic polyurethane
Cycoloy EHA	Borg-Warner Chemicals Inc.	ABS + PC	Acrylonitrile/butadiene/styrene + polycarbonate
Cycovin K	Borg-Warner Chemicals Inc.	ABS + PVC	Acrylonitrile/butadiene/styrene + polyvinyl chloride
Cymel	American Cyanamid Co.	MF	Melamine-formaldehyde
Cytor	Unknown	TPU	Polyurethane, thermoplastic
Daplen	Chemie Linz AG	PP	Polypropylene
Dapon	Chemie Linz AG	DAP	Poly (diallyl phthalate)

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TABLE 4.56 Common Plastics (*Continued*)

Common/trade name	Supplier	SAE symbol	Plastic "family" name
Delrin	E.I. Dupont de Nemours & Co.	POM	Polyoxymethylene: polyformaldehyde—"acetal"
Delrin AF	E.I. Dupont de Nemours & Co.	POM + PTFE	Polyoxymethylene + polytetra-fluoroethylene
Delrin ST	E.I. Dupont de Nemours & Co.	POM + RUBBER	Polyoxymethylene + rubber
Delrin T	E.I. Dupont de Nemours & Co.	POM + RUBBER	Polyoxymethylene + rubber
Derakane	Dow Chemical Co.	UP	Polyester, thermoset (unsaturated)
Desmopan	Bayer AG	PUR	Polyurethane, thermoset (unsaturated)
Diakon	ICI Hyde Group	PMMA	Poly (methyl methacrylate)—"acrylic"
Diaron	Reichold Chemicals Inc.	MF	Melamine-formaldehyde
DKE + 450	Sumitoma Corp. of America	PVC + PMMA	Polyvinyl chloride = polymethyl methacrylate
Duraflex	Shell Chemical Co.	PB	Polybutene-1
Durathon	Bayer AG	PS	Polystyrene
Durel	Celanese Engineering Resins	PAT	Polyester, thermoplastic—"polyarylate"
Durethan	Bayer AG	PA	Polyamide—"nylon"
Durez	Occidental Chemical Corp.	DAP	Poly (diallyl phthalate)
Durez	Occidental Chemical Corp.	PF	Phenol-formaldehyde
Durilite	Unknown	EC	Ethyl cellulose
Dylan	Arco Chemical Co.	PE	Polyethylene
Dylark	Arco Chemical Co.	SMA	Styrene/maleic anhydride
Dylark	Arco Chemical Co.	SMA + PS	Styrene/maleic anhydride + high impact polystyrene
Dylen	Arco Chemical Co.	PS	Polystyrene
Dynyl	Phone Poulenc Inc.	PEBA	Thermoplastic polyester—"polyether block amide"
Econol	Sohio Chemical Co.	PAT	Polyester, thermoplastic—"polyarylate"
Elkcel	Carborundum Co.	POB	Poly-*p*-oxybenzoate
Elemid	Borg-Warner Chemicals Inc.	ABS + PA	Acrylonitrile/butadiene/styrene + polyamide
Elexar	Shell Chemical Co.	SB	Styrene-butadiene

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Elexar	Shell Chemical Co.	TES	Thermoplastic elastomer—"styrene block copolymer"
Elvax	E.I. Dupont de Nemours & Co.	EVAC	Ethylene/vinyl acetate
Envex	Rogers Corp.	PI	Polyamide
Epon	Shell Chemical Co.	EP	Epoxide: epoxy
Epotuf	Reichold Chemicals Inc.	EP	Epoxide: epoxy
Escorene	Exxon Chemical Americas	PE	Polyethylene
Escorene	Exxon Chemical Americas	PP	Polypropylene
Estamid (ester)	Dow Chemical Co.	PEBA	Polyester, thermoplastic—"polyether block amide"
Estane	B.G. Goodrich Chemical Group	ABS + TPU	Acrylonitrile/butadiene/styrene + thermoplastic polyurethane
Estane	B.G. Goodrich Chemical Group	TPU	Thermoplastic elastomer—"polyurethane"
Ethocel	Dow Chemical Co.	CA	Cellulose acetate
Ethocel	Dow Chemical Co.	CAB	Cellulose acetate butyrate
Ethocel	Dow Chemical Co.	CAP	Cellulose acetate propionate
Ethocel	Dow Chemical Co.	CP	Cellulose propionate
Ethocel	Dow Chemical Co.	EC	Ethyl cellulose
Evanol	Unknown	PVAL	Poly (vinyl alcohol)
Ferroflex	Ferro Corp.	TPO	Thermoplastic elastomer—"polyolefinic"
Fluon	ICI Americas Inc.	PTFE	Polytetrafluoroethylene
Fluorocomp	LNP Corp./ICI Americas	FEP	Perfluoro (ethylene/propylene)
Formion	A. Schulman Inc.	EMA	Ethylene methacrylate acid
Formvar	Monsanto Co.	PVFM	Poly (vinyl formal)
Forsacryl	Unknown	SAN	Styrene-acrylonitrile
Fortiflex	Soltex Polymer Corp.	PE	Polyethylene
Fortron	Celanese Engineering Resins	PPS	Poly (phenylene sulfide)
Geloy 1200	General Electric Co.	ASA + PVC	Acrylonitrile/styrene/acrylate + polyvinyl chloride
Geloy 1320	General Electric Co.	ASA + PMMA	Acrylonitrile/styrene/acrylate + polymethyl methacrylate
Gelva	Monsanto Co.	PVAC	Poly (vinyl acetate)
Gelvatol	Monsanto Co.	PVAL	Poly (vinyl alcohol)
Gemax	General Electric Co.	PBT + PPE	Polybutylene terephthalate + polyphenylene ether

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TABLE 4.56 Common Plastics (*Continued*)

Common/trade name	Supplier	SAE symbol	Plastic "family" name
Gemon	General Electric Co.	PI	Polyimide
Geon	B.G. Goodrich Chemical Group	PVC	Poly (vinyl chloride)
Geon	B.G. Goodrich Chemical Group	VCVDC	Vinyl chloride/vinylidene chloride
Gracon	W.R. Grace Co.	PVC	Poly (vinyl chloride)
Grilon	Emser Industries Inc.	PA + RUBBER	Polyamide + rubber
Halon	Allied Engineered Plastics	PCTFE	Polychlorotrifluoroethylene
Halon	Allied Engineered Plastics	PTFE	Polytetrafluoroethylene
Hi-Fax	Himont U.S.A. Inc.	PE	Polyethylene
Hostadur	American Hoechst Corp.	PET	Polyester, thermoplastic—"polyethylene terephthalate"
Hostaflon	American Hoechst Corp.	PTFE	Polytetrafluoroethylene
Hostaform	American Hoechst Corp.	POM	Polyoxymethylene: polyformaldehyde—"acetal"
Hostalen	American Hoechst Corp.	PE	Polyethylene
Hostalen	American Hoechst Corp.	PEOX	Poly (ethylene oxide)
Hostalen	American Hoechst Corp.	PP	Polypropylene
Hostalite Z	American Hoechst Corp.	PVC + CPE	Polyvinyl chloride + chlorinated polyethylene
Hycar	B.G. Goodrich Chemical Group	PVC + NBR	Polyvinyl chloride + nitrile butadiene rubber
Hytrel	E.I. Dupont de Nemours & Co.	TEEE	Thermoplastic elastomer—"ether ester block copolymer"
Impet	Celanese Engineering Resins	PET	Polyester thermoplastic—"poly (ethylene terephthalate)"
Ionomer	Generic name	EMA	Ethylene/methacrylic acid
Isomin	Unknown	MF	Melamine-formaldehyde
Isoplast	Dow Chemical Co.	RTPU	Thermoplastic elastomer—"rigid polyurethane"
Kadel	Amoco Chemicals Corp.	PEEK	Polyether-etherketone
Kamax	Rohm & Haas Co.	PI	Polyamide
Kel-F	3M Company	PCTFE	Polychlorotrifluoroethylene
Kinel	Rhone Poulenc Inc.	PI	Polyamide

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Kralastic FVM	Uniroyal Inc.	ABS + PVC	Acrylonitrile/butadiene/styrene + polyvinyl chloride
Kraton	Shell Chemical Co.	TES	Thermoplastic elastomer—"styrene block copolymer"
Kydex	Rohm & Haas Co.	PVC + PMMA	Polyvinyl chloride + polymethyl methacrylate
Kynar	Pennwalt Corp.	PVDF	Poly (vinylidene fluoride)
K-Resins	Phillips Chemical Co.	SB	Styrene-butadiene
Lexan	General Electric Co.	PC	Polycarbonate plastics
Lexan	General Electric Co.	PC + PE	Polycarbonate + polyethylene
Lomod	General Electric Co.	TEEE	Thermoplastic elastomer—"ether ester block copolymer"
Lupolen	BASF Wyandotte Corp.	PE	Polyethylene
Luran	BASF Wyandotte Corp.	ASA	Acrylonitrile/styrene/acrylate
Luran	BASF Wyandotte Corp.	SAN	Styrene/acrylonitrile
Lustran	Monsanto Co.	ABS	Acrylonitrile/butadiene/styrene
Lustran	Monsanto Co.	ABS + PVC	Acrylonitrile/butadiene/styrene + polyvinyl chloride
Lustran	Monsanto Co.	SAN	Styrene/acrylonitrile
Lustrex	Polysar Inc.	PS	Polystyrene
Luvican	BASF Wyandotte Corp.	PVK	Polyvinylcarbazole
Macroblend	Mobay Chemical Corp.	PC + PBT	Polycarbonate + polybutylene terephthalate
Macroblend	Mobay Chemical Corp.	PC + PET	Polycarbonate + polyethylene terephthalate
Macrolon	Mobay Chemical Corp.	PC	Polycarbonate plastics
Marlex	Phillips Chemical Co.	PE	Polyethylene
Marlex	Phillips Chemical Co.	PP	Polypropylene
Melmac	Phillips Chemical Co.	MF	Melamine-formaldehyde
Merlon	Mobay Chemical Corp.	PC	Polycarbonate plastics
Merlon T	Mobay Chemical Corp.	PC + PE	Polycarbonate + polyethylene
Microthane	Unknown	EVAC	Ethylene/vinyl acetate
Mindel	Union Carbide Corp.	PARA	Polyarylamid (polyaramide)
Mindel	Union Carbide Corp.	PPSU	Poly (phenylene sulfone)
Mindel A	Union Carbide Corp.	ABS + PPSU	Acrylonitrile/butadiene/styrene + polyphenylene sulfone
Mindel B	Union Carbide Corp.	PET + PPSU	Polyethylene terephthalate + polyphenylene sulfone

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TABLE 4.56 Common Plastics (*Continued*)

Common/trade name	Supplier	SAE symbol	Plastic "family" name
Moplen	Himont-Italia	PP	Polypropylene
N5	Thermofil Inc.	PA + SAN	Polyamide + styrene/acrylonitrile
Nitrocellulose	Generic name	CN	Cellulose nitrate
None	—	AB	Acrylonitrile/butadiene
None	—	ABA	Acrylonitrile/butadiene/acrylate
None	—	AMMA	Acrylonitrile/methyl methacrylate
None	—	CF	Cresol formaldehyde
None	—	CMC	Carboxymethyl cellulose
None	—	CPVC	Chlorinated poly (vinyl chloride)
None	—	CS	Casein
None	—	EEA	Ethylene/ethyl acrylate
None	—	ETFE	Ethylene/tetrafluoroethylene
None	—	FF	Fluran formaldehyde
None	—	PA + EMA	Polyamide + ethylene methacrylic acid (ionomer)
None	—	PAE	Polyarylether
None	—	PB	Polybutene-1
None	—	PFF	Phenol furfurol
None	—	PPOX	Poly (propylene oxide)
None	—	PVCA	Poly (vinyl chloride acetate)
None	—	PVP	Polyvinylpyrrolidone
None	—	SI	Silicone
None	—	SMS	Styrene/A-methylstyrene
None	—	VCE	Vinyl chloride/ethylene
None	—	VCEMA	Vinyl chloride/ethylene/methyl acrylate
None	—	VCMA	Vinyl chloride/methyl acrylate

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Noryl	General Electric Co.	PPE	Polyphenylene ether plastics
Noryl	General Electric Co.	PPE + PS	Polyphenylene ether + high impact polystyrene
Noryl GTX	General Electric Co.	PA + PPE	Polyamide + polyphenylene ether
Novodur	Mobay Chemical Corp.	ABS	Acrylonitrile/butadiene/styrene
Novolen	BASF Wyandotte Corp.	PP	Polypropylene
Nycoa 1900	Nylon Corp. of America	PA + EMA	Polyamide + ethylene methacrylic acid—"ionomer"
Nydur BC	Unknown	PA + RUBBER	Polyamide + rubber
Nydur KL	Unknown	PA + RUBBER	Polyamide + rubber
Nylon	Generic name	PA	Polyamide—"nylon"
Oleflo	Avisun	PP	Polypropylene
Oppanol B	BASF Wyandotte Corp.	PIB	Polyisobutylene
Oroglas	Rohm & Haas Co.	PMMA	Poly (methyl methacrylate)—"acrylic"
Orthane	Eagle Picher Plastics Div.	TPU	Polyurethane, thermoplastic
Ozo	Unknown	PVC + NBR	Polyvinyl chloride + nitrile butadiene rubber
Paracril	Uniroyal Inc.	PVC + NBR	Polyvinyl chloride + nitrile butadiene rubber
Paxon	Allied Engineered Plastics	PE	Polyethylene
Pebax	Atochem U.S.A. Inc.	PEBA	Polyester, thermoplastic—"polyether block amide"
Pellethane	Dow Chemical Co.	ABS + TPU	Acrylonitrile/butadiene/styrene + thermoplastic polyurethane
Pellethane	Dow Chemical Co.	TPU	Thermoplastic elastomer—"polyurethane"
Penton	Hercules Inc.	CPE	Chlorinated polyethylene
Petlon	Mobay Chemical Corp.	PBT	Polyester, thermoplastic—"polybutylene terephthalate"
Petlon	Mobay Chemical Corp.	PET	Polyester, thermoplastic—"polyethylene terephthalate"
Petra	Allied Engineered Plastics	PBT	Polyester, thermoplastic—"polybuthylene terephthalate"
Petra	Allied Engineered Plastics	PET	Polyester, thermoplastic—"polyethylene terephthalate"
Phenolic	Generic name	PF	Phenol-formaldehyde
Piso	Celanese Engineering Resins	PISU	Polymidesulfone
Plaskon	Plaskon Electronic Mtls. Inc.	UF	Urea-formaldehyde
Plenco	Plastics Engineering Co.	PF	Phenol-formaldehyde
Plexiglas	Rohm & Haas Co.	PMMA	Poly (methyl methacrylate)—"acrylic"

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TABLE 4.56 Common Plastics (*Continued*)

Common/trade name	Supplier	SAE symbol	Plastic "family" name
Pliolite	Goodyear Tire & Rubber Co.	SB	Styrene-butadiene
Pliovic	Goodyear Tire & Rubber Co.	PVC	Poly (vinyl chloride)
Pocan	Bayer AG/Mobay	PBT + RUBBER	"Polybutylene terephthalate" + rubber
Pocan B	Bayer AG/Mobay	PBT	Polyester, thermoplastic—"polybutylene terephthalate"
Polycomp	LNP Corp./ICI Americas	PPS + PTFE	Polyphenylene sulfide + fluoroethylene
Polyfort	A. Schulman Inc.	PE	Polyethylene
Polyfort	A. Schulman Inc.	PP	Polypropylene
Polypur	A. Schulman Inc.	TPU	Thermoplastic elastomer—"polyurethane"
Polystyrol	BASF Wyandotte Corp.	PS	Polystyrene
Polystyrol	BASF Wyandotte Corp.	SB	Styrene/butadiene
Polystyrol SB	BASF Wyandotte Corp.	PS	Polystyrene, high impact
Polytrope	A. Schulman Inc.	TPO	Thermoplastic elastomer—"polyolefinic"
Polyvin	A. Schulman Inc.	PVC	Poly (vinyl chloride)
Poly-Dap	DAP	DAP	Poly (diallyl phthalate)
Premi-Glas	Premix Inc.	UP	Polyester, unsaturated thermoset
Prevex	Borg-Warner Chemicals Inc.	PPE	Polyphenylene ether plastics
Prevex	Borg-Warner Chemicals Inc.	PPE + PS	Polyphenylene ether + high impact polystyrene
Profax	Himont U.S.A. Inc.	PP	Polypropylene
Proloy	Borg-Warner Chemicals Inc.	ABS + PC	Acrylonitrile/butadiene/styrene + polycarbonate
Pyralin	E.I. Dupont de Nemours & Co.	PI	Polyimide
Radel	Union Carbide Corp.	PPSU	Polyphenylene sulfone
Renflex	Research Polymers Inc.	TPO	Thermoplastic elastomer—"polyolefinic"
Rilsan	Atochem U.S.A. Inc.	PA	Polyamide—"nylon"
Riteflex BP	Celanese Engineering Resins	TEEE	Thermoplastic elastomer—"ether ester block copolymer"
Ropet	Rohm & Haas Co.	PET + PMMA	Polyethylene terephthalate + polymethyl methacrylate

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Rovel	Dow Chemical Co.	AES	Acrylonitrile/ethylene/styrene
Rynite	E.I. Dupont de Nemours & Co.	PBT	Polyester, thermoplastic—"polybutylene terephthalate"
Rynite	E.I. Dupont de Nemours & Co.	PET	Polyester, thermoplastic—"polybutylene terephthalate"
Rynite SST	E.I. Dupont de Nemours & Co.	PET + RUBBER	Polyethylene terephthalate + rubber
Ryton	Phillips Chemical Co.	PPS	Poly (phenylene sulfide)
Santoprene	Monsanto Co.	TPO	Thermoplastic elastomer—"polyolefinic"
Saran	Dow Chemical Co.	PVDC	Poly (vinylidene chloride)
Selar	E.I. Dupont de Nemours & Co.	PA + PE	Polyamide + polyethylene
Selectron	PPG Industries Inc.	UP	Polyester unsaturated thermoset
Skanopal	Penstorp Inc.	UF	Urea-formaldehyde
Skybond	Monsanto Co.	PI	Polyimide
SMC	Generic name	UP	Polyester, thermoset (unsaturated)
Solair	Soltex Polymer Corp.	PE	Polyethylene
Spectrim	Dow Chemical Co.	PUR	Polyurethane, thermoset
Styrolux	Westlake Plastics Co.	SB	Styrene-butadiene
Styron	Dow Chemical Co.	PS	Polystyrene
Surlyn	E.I. Dupont de Nemours & Co.	EMA	Ethylene/methacrylic acid—"ionomer"
Tedlar	E.I. Dupont de Nemours & Co.	PVF	Poly (vinyl fluoride)
Teflon	E.I. Dupont de Nemours & Co.	FEP	Perfluoro (ethylene/propylene)
Teflon	E.I. Dupont de Nemours & Co.	PTFE	Polytetrafluoroethylene
Teflonz	E.I. Dupont de Nemours & Co.	FEP	Tetrafluoroethylene/hexafluoro propylene
Teflonz	E.I. Dupont de Nemours & Co.	FEP	Tetrafluoroethylene/hexafluoro propylene
Telcar	Teknor Apex Co.	TPO	Thermoplastic elastomer—"polyolefinic"
Tenite	Eastman Chemical Products Inc.	CA	Cellulose acetate
Tenite	Eastman Chemical Products Inc.	CAB	Cellulose acetate butyrate
Tenite	Eastman Chemical Products Inc.	CAP	Cellulose acetate propionate
Tenite	Eastman Chemical Products Inc.	CP	Cellulose propionate
Tenite	Eastman Chemical Products Inc.	PP	Polypropylene
Terblend SKR	BASF Wyandotte Corp.	ASA + PC	Acrylonitrile/styrene/acrylate + polycarbonate

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TABLE 4.56 Common Plastics (*Continued*)

Common/trade name	Supplier	SAE symbol	Plastic "family" name
Terlukan	Bayer AG	ABS	Acrylonitrile/butadiene/styrene
Tetran	Pennwalt Corp.	PTFE	Polytetrafluoroethylene
Texin	Mobay Chemical Corp.	PC + TPU	Polycarbonate + thermoplastic polyurethane
Texin	Mobay Chemical Corp.	TPU	Polyurethane, thermoplastic
Thermo	Unknown	CPE	Chlorinated polyethylene
Thermocomp AL	LNP Corp./ICI Americas	AS + PTFE	Acrylonitrile/butadiene/styrene + polytetra fluoroethylene
Thermocomp KL	LNP Corp./ICI Americas	POM + PTFE	Polyoxymethylene + polytetra fluoroethylene
Torlon	Amoco Chemicals Corp.	PAI	Polyamide-imide
TPE	Generic name	—	Thermoplastic elastomer
TPX	Mitsui & Co.	PMP	Poly (4-methylpentene-1)
Triax 1000	Monsanto Co.	ABS + PA	Acrylonitrile/butadiene/styrene + polyamide
Trosiplast	Kay-Fries Inc.	PVC	Poly (vinyl chloride)
Tuf-Flex	American Hoechst Corp.	PS	Polystyrene, high impact
Tyril	Dow Chemical Co.	SAN	Styrene/acrylonitrile
Tyrin	Dow Chemical Co.	CPE	Chlorinated polyethylene
Udel	Union Carbide Corp.	PPSU	Poly (phenylene sulfone)
Ultadur	BASF Wyandotte Corp.	PET	Poly (ethylene terephthalate)
Ultaform	BASF Wyandotte Corp.	POM	Polyoxymethylene: polyformaldehyde—"acetal"
Ultamid KR	BASF Wyandotte Corp.	PA + RUBBER	Polyamide + rubber
Ultem	General Electric Co.	PEI	Polyetherimide
Ultradur	BASF Wyandotte Corp.	PBT	Polyester, thermoplastic—"polybutylene terephthalate"
Ultradur KR	BASF Wyandotte Corp.	PBT + RUBBER	Polybutylene terephthalate + rubber
Ultramid	BASF Wyandotte Corp.	PA	Polyamide—"nylon"

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Ultrason	BASF Wyandotte Corp.	PESU	Polyether sulfone
Ultrason	BASF Wyandotte Corp.	PPSU	Poly (phenylene sulfone)
Ultrex	Spiratex Co.	PE	Polyethylene
Unichem	Colorite Plastics Co.	PVC	Poly (vinyl chloride)
Uyex	Eastman Chemical Products Inc.	CAB	Cellulose acetate butyrate
Valox	General Electric Co.	PBT	Polyester, thermoplastic—"polybutylene terephthalate"
Valox	General Electric Co.	PBT + PET	Polybutylene terephthalate + "polyethylene terephthalate"
Valox	General Electric Co.	PBT + RUBBER	Polybutylene terephthalate + rubber
Valox	General Electric Co.	PC + PBT	Polycarbonate + polybutylene terephthalate
Valox	General Electric Co.	PC + PET	Polycarbonate + terephthalate
Valox	General Electric Co.	PET	Polyester, thermoplastic—"polyethylene terephthalate"
Vandor PB	Celanese Engineering Resins	PBT + RUBBER	Polybutylene terephthalate + rubber
Vectra	Celanese Engineering Resins	ARP	Polyester, thermoplastic—"liquid crystal polymer"
Vedril	Vedril Spa (Spanish)	PMMA	Poly (methyl methacrylate)—"acrylic"
Vespel	E.I. Dupont de Nemours & Co.	PARA	Polyarylamid (polyaramide)—"aramid"
Vespel	E.I. Dupont de Nemours & Co.	PI	Polyimide
Vibrin-Mat	U.S. Rubber Co.	UP	Polyester, thermoset (unsaturated)
Victrex	ICI Americas Inc.	PESU	Polyethersulfone
Victrex Peek	ICI Americas Inc.	PEEK	Polyetherketone
Victrex Pek	ICI Americas Inc.	PEK	Polyetherketone
Vinoflex	BASF Wyandotte Corp.	PVC	Poly (vinyl chloride)
Vinylite	Canadian Resins & Chemical Ltd	PVAC	Poly (vinyl acetate)
Vinylite	Canadian Resins & Chemical Ltd	PVB	Poly (vinyl butyral)
Vinylite	Canadian Resins & Chemical Ltd	PVC	Poly (vinyl chloride)
Vinylite	Canadian Resins & Chemical Ltd	VCVAC	Vinyl chloride/vinyl acetate
Vistaflex	Esso Chemicals (Europe)	TPO	Thermoplastic elastomer—"polyolefinic"

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TABLE 4.56 Common Plastics (*Continued*)

Common/trade name	Supplier	SAE symbol	Plastic "family" name
Vydyne	Monsanto Co.	PA	Polyamide "nylon"
Vynite	Allied Engineered Plastics	PVC + NBR	Polyvinyl chloride + nitrile butadiene rubber
Vythene	Alpha Chemicals & Plastics CRP	PVC + PU	Polyvinyl chloride + polyurethane
Wellamid	Wellman Inc.	PA	Polyamide—"nylon"
Wellite	Wellman Inc.	PBT	Polyester, thermoplastic—"polybutylene terephthalate"
Wellpet	Wellman Inc.	PET	Polyester, thermoplastic—"polyethylene terephthalate"
Xenoy	General Electric Co.	PC + PBT	Polycarbonate + polybutylene terephthalate
XMC	Generic name	UP	Polyester, thermoset (unsaturated)—50% glass
Xydar	Dartco	ARP	Polyester, thermoplastic—"liquid crystal polymer"
Zytel	E.I. Dupont de Nemours & Co.	PA	Polyamide—"nylon"
Zytel ST	E.I. Dupont de Nemours & Co.	PA + RUBBER	Polyamide + rubber

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Polyimide

Polystyrene

Polysulfone

Polyurethane

Polyvinyl chloride (PVC)

RTV (room-temperature vulcanizing) silicones, Styrofoam (polystyrene)

Teflon (PTFE, polytetrafluoroethylene), urea-formaldehyde

Common plastics and typical uses

Acetal (Delrin, Celcon). *Properties:* High modulus of elasticity, low coefficient of friction, excellent abrasion and impact resistance, low moisture absorption, excellent machinability, ablative. *Typical uses*: Bearings, gears, antifriction parts, electrical components, washers, seals, insulators, and cams.

Acetate (Cellulose). *Properties*: Odorless, tasteless, nontoxic, grease resistant, high impact strength. *Typical uses*: Badges, blister packaging, displays, optical covers, and book covers.

Acrylic (Plexiglas, Lucite). *Properties*: Unusual optical clarity, high tensile strength, weatherability, good electrical properties, ablative. *Typical uses*: Displays, signs, models, lenses, and electrical and electronic parts.

Benelex (Laminate). *Properties*: High compressive strength, machinable, resists corrosion (alkalis or acids), good electrical insulation, high flexural, shear, and tensile strength. *Typical uses*: Work surfaces, electrical panels and switch gear, bus braces (low voltage only), and neutron shielding.

Diallyl phthalate, Melamine. *Properties*: High strength, chemical resistant, low water absorption, medium-high temperature use. *Typical uses*: Terminal blocks and strips, dishware, automotive applications, and aerospace applications.

Epoxy glass. *Properties*: High strength, high-temperature applications, flame retardant, low coefficient of thermal expansion, low water absorption. *Typical uses*: High-quality printed circuit boards, microwave stripline applications, VHF and UHF applications, electrical insulation, and service in temperature range –400 to 500°F.

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Mylar (polyester film, polyethylene terephthalate). *Properties*: High dielectric strength, chemical resistance, high mechanical strength, moisture resistant, temperature range 70 to 105°C, does not embrittle with age. *Typical uses*: Electrical and industrial applications and graphic arts applications.

Nylon. *Properties*: Wear resistant, low friction, high tensile strength, excellent impact resistance, high fatigue resistance, easy machining, corrosion resistant, lightweight. *Typical uses*: Bearings, bushings, valve seats, washers, seals, cams, gears, guides, wheels, insulators, and wear parts.

Phenol formaldehyde (Bakelite). *Properties*: Wear resistant, rigid, moldable to precise dimensions, strong, excellent electrical properties, economical, will not support combustion. *Typical uses*: Electrical and electronic parts, handles, housings, insulator parts, mechanism parts, and parts that are to resist temperatures to 250°C.

Phenolic laminates. *Properties*: Immune to common solvents, lightweight, strong, easily machined. *Typical uses*: Bearings, machined parts, insulation, gears, cams, sleeves, and electrical and electronic parts.

Polycarbonate (Lexan). *Properties*: Virtually unbreakable, weather resistant, optically clear, lightweight, self-extinguishing, thermoformable, machinable, solvent cementable. *Typical uses*: High-voltage insulation, impact resistant injection moldings, glazing, bulletproof, glazing, and plumbing fittings. The strongest thermoplastic.

Polyester glass. *Properties*: Extremely tough, high dielectric strength, heat resistant, low water absorption, antitracking electrically, self-extinguishing, machinable. *Typical uses*: Insulators and bus braces, switch phase barriers, general electrical insulation, mechanical insulated push rods for switches and breakers, contact blocks, and terminal blocks.

Polyethylene. *Properties*: Transparent in thin sheets, water resistant. *Typical uses*: Bags for food storage, vapor barriers in construction, trays, rollers, gaskets, seals, and radiation shielding.

Polypropylene. *Properties*: Good tensile strength, low water absorption, excellent chemical resistance, stress-crack resistant, electrical properties. *Typical uses*: Tanks, ducts, exhaust systems, gaskets, laboratory and hospital ware, wire coating, and sporting goods.

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Polystyrene. *Properties*: Outstanding electrical properties, excellent machinability, ease of fabrication, excellent chemical resistance, oil resistant, clarity, rigidity, hardness, dimensional stability. *Typical uses*: Lighting panels, tote boxes, electronic components, door panels (refrigerators), drip pans, displays, and furniture components.

Polysulfone. *Properties*: Tough, rigid, high-strength, high-temperature thermoplastic, temperature range –150 to +300°F, excellent electrical characteristics, good chemical resistance, low creep and cold-flow properties, capable of being autoclaved repeatedly. *Typical uses*: Food-processing and medical industries, electrical and electronics, appliance, automotive, aircraft, and aerospace uses.

Polyurethane. *Properties*: Elastomeric to rock-hard forms available, high physical characteristics, toughness, durability, broad hardness range, withstands severe use, abrasion resistant, weather resistant, radiation resistant, temperature range –80 to 250°F, resistant to common solvents, available also in foam types. *Typical uses*: Replaces a host of materials that are not performing well; extremely broad range of usage; replaces rubber parts, plastic parts, and some metallic parts.

Polyvinyl chloride (PVC). *Properties*: Corrosion resistant, formable, lightweight, excellent electrical properties, impact resistant, low water absorption, cementable, machinable, weldable. *Typical uses*: Machined parts, nuts, bolts, PVC pipe and fittings, valves, and strainers.

RTV silicone rubber. *Properties*: Resistant to temperature extremes (–75 to 400°F), excellent electrical characteristics, weather resistant, good chemical resistance; FDA, USDA, and UL approved. *Typical uses*: General-purpose high-quality sealant, gasket cement, food contact surfaces, electrical insulation, bonding agent, glass-tank construction, and countless other applications.

Styrofoam. *Properties*: Low water absorption, floats, thermal insulator, extremely lightweight. *Typical uses*: Insulation board for homes and buildings, cups, containers, thermos containers, shock-absorbing packaging, plates (food), and flotation logs.

Teflon (PTFE). *Properties*: Unexcelled chemical resistance, cryogenic service, electrical insulation, very low friction, high dielectric strength, very low dissipation factor, very high resistivity, machinability. *Typical uses*: Valve components, gaskets (with caution, due

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to cold flow), pump parts, seal rings, insulators (electrical), terminals, bearings, rollers, bushings, electrical tapes, plumbing tapes, and machined parts; bondable with special etchant preparations.

Urea-formaldehyde. *Properties*: Hard, strong, molds accurately, low water absorption, excellent electrical properties, ablative, economical, will not support combustion. *Typical uses*: Electrical and electronic parts, insulators, small parts, and housings.

4.9 Properties of Materials: General and Specific

Table 4.57 lists the properties of various metals and alloys. Table 4.58 lists the properties of other metals and alloys. Table 4.59 lists the coefficients of linear expansion for common materials. Table 4.60 lists the chemical symbols for metals.

4.10 Material Specification Sheets and Analysis Reports

All manufacturers of plastic materials provide material specification sheets when so requested. Material analysis sheets likewise are supplied by metal providers, forges, and foundries when so requested. The material test report is generated by one of the various materials test laboratories nationwide, but it must be purchased by the company requesting the analysis. Owing to the rise in imported materials that may or may not meet the requirements of the SAE, ASTM, AISI, ASM, and ANSI standards, material confirmation by way of laboratory analysis is necessary in many instances. Materials that do not conform to the standards applicable for a given material, as specified on the engineering drawings, pose a serious safety problem for manufacturers of industrial and consumer products and their users. When in doubt about a material's performance, have the material analyzed at a testing laboratory. The material supplier is responsible for the specifications of the material that it sells. If you order a type 304L stainless steel per SAE or ASTM specifications, the material must conform to these specifications both chemically and mechanically.

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TABLE 4.57 Properties of Various Metals and Alloys

Material	Relative resistivity* at 20°C	Density, g/cm^3	Thermal conductivity at 20°C, W/cm·°C	Thermal expansion $\times 10^{-6}$/°C, in	Melting, °C
Aluminum	1.54	2.70	2.22	23.6	660
Beryllium	2.3	1.85	1.46	11.6	1277
Bismuth	67.0	9.80	0.084	13.3	271
Brass, yellow	3.7	8.47	1.17	20.3	930
Cadmium	4.3	8.65	0.92	29.8	321
Carbon, graphite	790	2.25	0.24	0.6–4.3	Sublimes
Chromium	7.4	7.19	0.67	6.2	1875
Cobalt	3.6	8.85	0.69	13.8	1495
Columbium (see Niobium)					
Constantan	29.0	8.9	0.21	14.9	1290
Copper, hard drawn	1.03	8.94	3.91	16.8	1083
Gallium	4.7	5.91	0.29	18.0	30
Germanium	2.7×10^6	5.33	0.59	5.75	937
Gold	1.36	19.32	2.96	14.2	1063
Inconel, 17–16–8	56.9	8.51	0.15	11.5	1425
Indium	4.9	7.31	0.24	33.0	156
Invar, 64–36	46.0	8.00	0.11	0–2	1425
Iron	5.6	7.87	0.75	11.8	1536
Lead	12.0	11.34	0.35	29.3	327
Magnesium	2.58	1.74	1.53	27.1	650
Mercury	55.6	13.55	0.082	—	–38.9
Molybdenum	3.3	10.22	1.42	4.9	2610
Monel, 67–30	27.9	8.84	0.26	14.0	1325
Nichrome, 80–20	62.5	8.4	0.134	13.0	1400
Nickel	5.5	8.89	0.61	13.3	1440
Niobium	7.2	8.57	0.52	7.31	2468
Palladium	6.3	12.02	0.70	11.8	1552
Phosphor bronze 95–5	6.4	8.86	0.71	17.8	1000
Platinum, 99.9%	6.16	21.45	0.69	8.9	1769
Silicon	10^{11}	2.33	1.25	2.5	1420
Silver	0.922	10.49	4.18	19.7	961
Steel, 0.4–0.5 C	7–12	7.8	0.5	11.0	1480
Steel, stainless 304	42	7.9	0.16	17.0	1430
Steel, stainless 410	33	7.7	0.24	11	1500
Tantalum	7.4	16.6	0.54	6.6	3000
Thorium	8.1	11.6	0.37	12.5	1750
Tin	7.0	7.30	0.63	23	232
Titanium	24.2	4.51	0.41	8.4	1670
Tungsten	3.2	19.3	1.67	4.6	3410
Uranium	17.5	18.7	0.3	6.8–14.1	1132
Zinc	3.5	7.14	1.10	27	420
Zirconium	23	6.5	0.21	5.8	1852

* Standard resistivity of 100% IACS copper at 20°C = 1.7241×10^{-6} Ω·cm.

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TABLE 4.58 Other Common Metals and Alloys

Metal	Density, g/cm^3	Weight, lb/in^3	Young's modulus (E), tension, lb/in^2	Torsional modulus (G), lb/in^2	Poisson's ratio	Electrical resistivity, Ω·cm
Aluminum (pure)	2.70	0.098	9×10^6	—	0.33	2.6×10^{-6}
Aluminum alloy (high strength)	2.78	0.101	$10–11 \times 10^6$	—	0.33	2.8×10^{-6}
Antimony	6.69	0.242	11.3×10^6	2.9×10^6	—	3.1×10^{-6}
Beryllium copper (C170) alloy	8.4	0.303	19×10^6	—	0.29	3.1×10^{-6}
Bismuth	9.75	0.352	—	—	—	119×10^{-6}
Brass (80Cu/20Zn)	8.6	0.311	16×10^6	6×10^6	0.34	7×10^{-6}
Cadmium	8.65	0.312	10.1×10^6	3.5×10^6	—	7.5×-6
Cast iron (gray)	7.2	0.260	14×10^6	5.6×10^6	0.21	—
Chromium	7.19	0.260	—	—	—	2.6×10^{-6}
Copper	8.96	0.324	17×10^6	6.4×10^6	0.34	1.72×10^{-6}
Gold	19.32	0.698	11.4×10^6	—	—	2.44×10^{-6}
Iron	7.87	0.284	28×10^6	11.2×10^6	0.30	10×10^{-6}
Iron (malleable)	7.85	0.284	25×10^6	11.5×10^6	0.17	—
Lead	11.35	0.410	2.4×10^6	—	0.43	22×10^{-6}
Lithium	0.53	0.019	—	—	—	9×10^{-6}
Magnesium (cast)	1.74	0.063	6.5×10^6	2.4×10^6	0.35	44×10^{-6}
Mercury	13.55	0.490	—	—	—	96×10^{-6}
Molybdenum	10.22	0.369	—	—	—	5.7×10^{-6}
Nickel	8.90	0.322	30×10^6	10.6×10^6	0.32	7.8×10^{-6}
Palladium	12.02	0.434	—	—	—	11×10^{-6}
Phosphor bronze	8.90	0.322	16×10^6	6×10^6	0.35	10×10^{-6}
Platinum	21.45	0.775	24.2×10^6	9.3×10^6	—	10×10^{-6}
Silver	10.50	0.379	11.2×10^6	3.8×10^6	—	1.6×10^{-6}
Steel (medium) carbon)	7.80	0.282	30×10^6	11.4×10^6	0.30	15×10^{-6}
Steel (stainless 300 type)	8.03	0.290	28×10^6	11.4×10^6	0.28	30×10^{-6}
Steel (stainless 400 type)	7.75	0.280	29×10^6	12.6×10^6	0.28	30×10^{-6}
Tin	7.31	0.264	7×10^6	2.4×10^6	—	11.5×10^{-6}
Titanium	4.54	0.164	16×10^6	—	—	—
Tungsten	19.30	0.697	51.5×10^6	21.5×10^6	—	5.51×10^{-6}
Zinc	7.13	0.258	14.5×10^6	5×10^6	0.11	6×10^{-6}

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TABLE 4.59 Coefficients of Linear Expansion for Common Materials

Metal, alloy, or other material	Linear expansion	
	in per 1°F	in per 1°C
Aluminum, wrought	0.0000128	0.0000231
Brass	0.0000104	0.0000188
Bronze	0.0000101	0.0000181
Copper	0.0000093	0.0000168
Cast iron, gray	0.0000059	0.0000106
Wrought iron	0.0000067	0.0000120
Lead	0.0000159	0.0000286
Magnesium alloy	0.0000160	0.0000290
Nickel	0.0000070	0.0000126
Cast steel	0.0000061	0.0000110
Hard steel	0.0000073	0.0000132
Medium steel	0.0000067	0.0000120
Soft steel	0.0000061	0.0000110
Stainless steel	0.0000099	0.0000178
Zinc, rolled	0.0000173	0.0000263
Concrete	0.0000079	0.0000143
Granite	0.0000047	0.0000084
Marble	0.0000056	0.0000100
Plaster	0.0000092	0.0000166
Slate	0.0000058	0.0000104
Fir	0.0000021	0.0000037
Maple	0.0000036	0.0000064
Oak	0.0000027	0.0000049
Pine	0.0000030	0.0000054
Plate glass	0.0000050	0.0000089
Hard rubber	0.0000044	0.0000080
Porcelain	0.0000009	0.0000016
Silver	0.0000104	0.0000188
Tin	0.0000148	0.0000269
Tungsten	0.0000024	0.0000043

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TABLE 4.60 Chemical Symbols for Metals

Metal	Symbol	Metal	Symbol
Aluminum	Al	Manganese	Mn
Antimony	Sb	Mercury	Hg
Beryllium	Be	Molybdenum	Mo
Bismuth	Bi	Nickel	Ni
Boron	B	Platinum	Pt
Cadmium	Cd	Selenium	Se
Carbon	C	Silicon	Si
Chromium	Cr	Silver	Ag
Cobalt	Co	Tellurium	Te
Copper	Cu	Tin	Sn
Gold	Au	Titanium	Ti
Iridium	Ir	Tungsten	W
Iron	Fe	Vanadium	V
Lead	Pb	Zinc	Zn
Lithium	Li	Zirconium	Zr
Magnesium	Mg		

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Chapter

5

Modern Engineering Drawing Practices

Modern engineering drawing practices have been greatly influenced by the widespread acceptance of computer-aided design (CAD) packages. Although these systems have greatly simplified the process of documenting dimensions, tolerances, and other important information, having a basic understanding of drawing practices is still essential. This chapter also covers procedures for determining limits and fits on hole/shaft systems because this is an important activity related to dimensioning and tolerancing.

5.1 General Dimensioning and Tolerancing Practices

Our definition of *tolerance* is the amount of dimensional variation allowed on a part or assembly of parts. Tolerance is equal to the difference between maximum and minimum limits of the specified dimension. For example:

5.000 ± 0.010 has a tolerance of 0.020

$\dfrac{5.000}{4.995}$ has a tolerance of 0.005

$\dfrac{6.129}{6.121}$ has a tolerance of 0.008

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Unilateral and bilateral tolerances. Unilateral tolerance is used to relate the total tolerance to a basic dimension in one direction only. For example:

$$5.000^{+0.002}_{-0.000} \quad \text{(positive unilateral)}$$

$$5.000^{+0.000}_{-0.002} \quad \text{(negative unilateral)}$$

Bilateral tolerance is used to relate the total tolerance to a basic dimension in both plus and minus directions. For example:

$$5.000 \pm 0.005 \quad (\text{tolerance} = 0.010)$$

$$5.000^{+0.002}_{-0.006} \quad (\text{tolerance} = 0.008)$$

Showing dimensional tolerances in an over-and-under form is as illustrated:

For shafts: $\dfrac{5.005}{4.995}$ (larger dimension "over") $T = 0.010$

For holes: $\dfrac{5.002}{5.007}$ (smaller dimension "over") $T = 0.005$

Tolerancing practices. Tolerances are applied to show the permissible variation in the direction that is the least critical. If variation in either direction is equally critical, the bilateral tolerance is used. If a variation in one direction is more critical than a variation in another direction, the unilateral tolerance should be given in the least critical direction.

For example, if you want the diameter of a round rod not to exceed 3.000 in but will allow it to go under to 2.995 in, this is the same as stating

$$3.000^{+0.000}_{-0.005}$$

Tolerances on the centerline distances between holes in a part are usually bilateral.

For nonmating surfaces, unilateral or bilateral tolerances can be used, but on mating surfaces, the tolerances should be unilateral in all but a few cases.

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Locating toleranced dimensions. A common baseline or point in each plane of a part should be used to establish dimensions.

5.1.1 Tolerance studies

At many companies, the design and checking groups perform on assembly drawings what is commonly referred to as a *tolerance study.* This is an in-depth analysis of all dimensions and tolerances on the detail parts to confirm the interchangeability of mass-produced parts going into the final product or subassembly.

The method generally followed to do the study involves comparing in combination all matching surfaces and hole-pattern dimensional tolerances at maximum and minimum conditions. If interference or mismatch occurs, the tolerances must be balanced to afford interchangeability of all parts and subassemblies.

This study is essential and critical when producing great quantities of parts to eliminate special fitting, which would destroy the ability to interchange parts.

A thorough designer will perform a tolerance study on the mechanism or assembly of parts and balance his or her tolerances on all dimensions to create interchangeability. For standard tolerances and fits, both English and metric, refer to ANSI B4.1-1967 (R 1999) and ANSI B4.2-1999.

Parts also must be toleranced to allow for electrodeposited finishes such as zinc plating, hard-coat anodizing, and Teflon coating. (See Chap. 13 for plating thicknesses.)

General tolerancing procedures, force fits, sliding fits, and so on are described in detail in the following standards references:

Dimensioning and tolerancing: ANSI/American Society of Mechanical Engineers (ASME) Y14.5M-1994

Standard limits and fits: ANSI B4.1-1967 (R 1999)

Basic metric fits: ANSI B4.2-1978 (R1999)

Geometric tolerancing: ANSI/ASME Y14.5M-1994

Surface texture: ANSI/ASME B46.1-2002

Drawing practices (surface texture): ANSI Y14.36-1978

5.1.2 Tolerance accumulation

The tolerance values resulting from the three methods of dimensioning parts or assemblies as shown in Fig. 5.1*a–c* are as follows. We will then have the following conditions:

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1. *Chain dimensioning.* The maximum variation between two features is equal to the sum of the tolerances on the intermediate distances. This results in the greatest tolerance accumulation (see Fig. 5.1*a*).
2. *Baseline dimensioning.* The maximum variation between two features is equal to the sum of the tolerances on the two dimensions from their origin to the features. This results in a reduction of the tolerance accumulation (see Fig. 5.1*b*).
3. *Direct dimensioning.* The maximum variation between two features is controlled by the tolerance on the dimension between the features. This results in the least tolerance (see Fig. 5.1*c*).

5.1.3 Dimensioning per ANSI/ASME Y14.5M-1994

ANSI Y14.5M-1994 covers dimensioning, tolerancing, and related practices for use on engineering drawings and related documents. The International System of Units (SI) is featured in this standard because SI units are expected to supersede U.S. customary units specified on engineering drawings. Nevertheless, it should be understood that U.S. customary units are equally applicable to this standard. Many U.S. companies and manufacturing facilities of all types still employ the U.S. customary or inch system.

Decimal dimensioning will be used on engineering drawings except where certain commercial commodities, such as pipe size, lumber size, and wire sizes, are identified.

Millimeter dimensioning

- When the dimension is less than 1 mm, a zero precedes the decimal point.
- Whole-number dimensions use neither a decimal point nor a zero following.
- On dimensions that exceed a whole number, the last digit to the right of the decimal point is not followed by a zero.

Note: The exception to the last rule is for bilateral tolerances or limits, where a zero is used by itself as part of the tolerance or limit.

Decimal-inch dimensioning. The decimal-inch system is explained in ANSI B87.1, and the following will be observed when specifying decimal-inch dimensions on engineering drawings:

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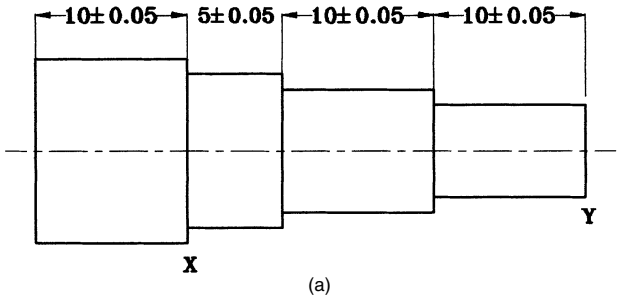
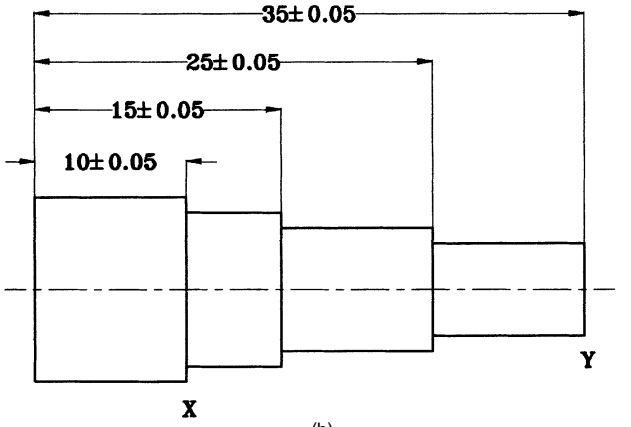
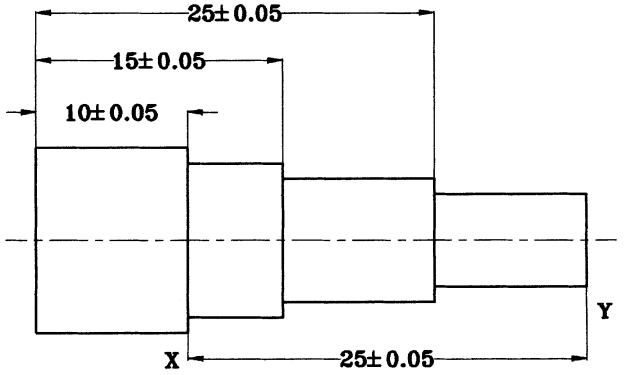


(a)



(b)



(c)

Figure 5.1 (*a*) Chain dimensioning—greatest tolerance accumulation between *X* and *Y*. (*b*) Baseline dimensioning—lesser tolerance accumulation between *X* and *Y*. (*c*) Direct dimensioning—least tolerance accumulation between *X* and *Y*.

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- A zero is not used *before* the decimal point for dimensional values of less than 1 in.
- A dimension is expressed to the same number of decimal places as its tolerance. Zeros are added to the right of the decimal point where necessary.
- Decimal points must be uniform and large enough to be clearly visible and meet the requirements of ANSI Y14.2M.
- The conversion and rounding of U.S. customary units are covered in ANSI Z210.1.

Glossary of terms—dimensioning and tolerancing. The following glossary of terms will be useful to the design engineer in that the use or recognition of these terms related to dimensioning and tolerancing will prevent misunderstanding between individuals and companies in relation to the meaning of these terms.

Actual size The measured size.

Basic dimension A numerical value used to describe the theoretically exact size, profile, orientation, or location of a feature or datum target. It is the basis from which permissible variations are established by tolerances on other dimensions, in notes, or in feature control frames.

Bilateral tolerance A tolerance in which variation is permitted in both directions from the specified dimension.

Datum A theoretically exact point, axis, or plane derived from the true geometric counterpart of a specified datum feature. A datum is the origin from which the location or geometric characteristics of features of a part are established.

Datum feature An actual feature of a part that is used to establish a datum.

Datum target A specified point, line, or area on a part used to establish a datum.

Dimension A numerical value expressed in appropriate units of measure and indicated on a drawing and in other documents along with lines, symbols, and notes to define the size or geometric characteristic, or both, of a part or part feature.

Feature The general term applied to a physical portion of a part, such as a surface, hole, or slot.

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Feature of size One cylindrical or spherical surface or a set of two plane parallel surfaces, each of which is associated with a size dimension.

Full indicator movement (FIM) The total movement of an indicator when applied appropriately to a surface to measure its variations.

Geometric tolerance The general term applied to the category of tolerances used to control form, profile, orientation, location, and runout.

Least-material condition (LMC) The condition in which a feature of size contains the least amount of material within the stated limits of size—for example, maximum hole diameter, minimum shaft diameter.

Limits of size The specified maximum and minimum sizes.

Maximum material condition (MMC) The condition in which a feature of size contains the maximum amount of material within the stated limits of size—for example, minimum hole diameter, maximum shaft diameter.

Reference dimension A dimension, usually without tolerance, used for information purposes only. It is considered auxiliary information and does not govern production or inspection operations. A reference dimension is a repeat of a dimension or is derived from other values shown on the drawing or on related drawings.

Regardless of feature size (RFS) The term used to indicate that a geometric tolerance or datum reference applies at any increment of size of the feature within its size tolerance.

Tolerance The total amount by which a specific dimension is permitted to vary. The tolerance is the difference between the maximum and minimum limits.

True position The theoretically exact location of a feature established by basic dimensions.

Unilateral tolerance A tolerance in which variation is permitted in one direction from the specified dimension.

Virtual condition The boundary generated by the collective effects of the specified MMC limit of size of a feature and any applicable geometric tolerances.

Applications of dimensions. Figures 5.2 through 5.24 show the applications of dimensions and dimension lines.

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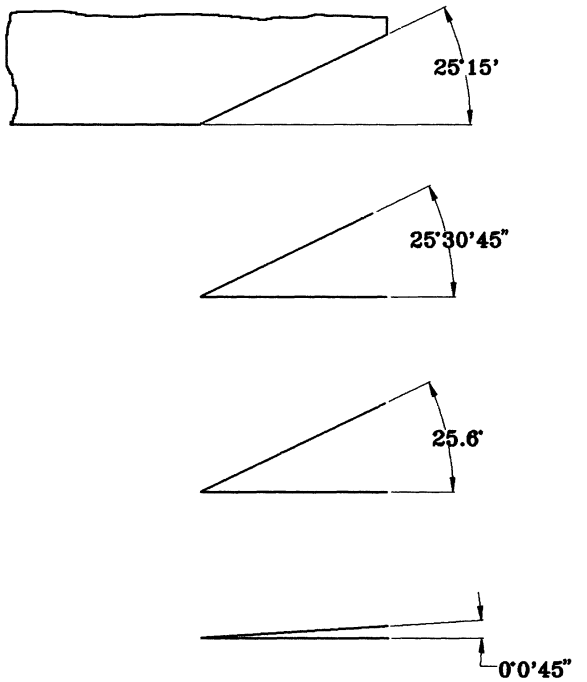

Figure 5.2 Angular units.

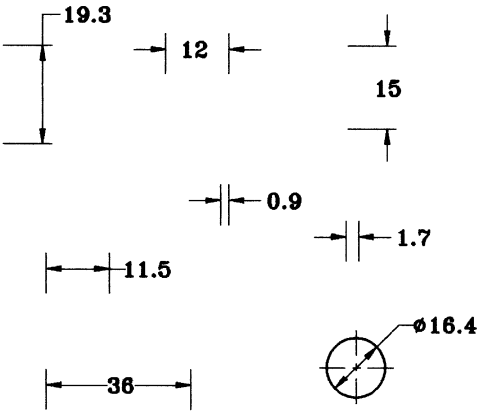

Figure 5.3 Millimeter dimensions.

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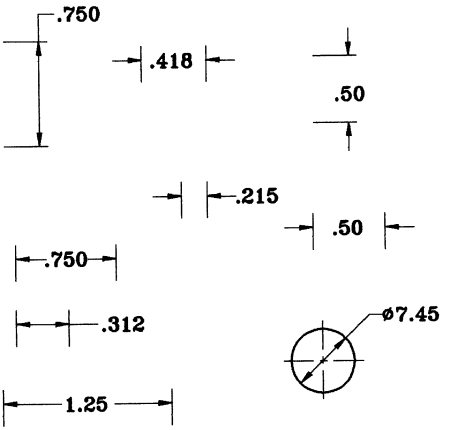

Figure 5.4 Decimal-inch dimensions.

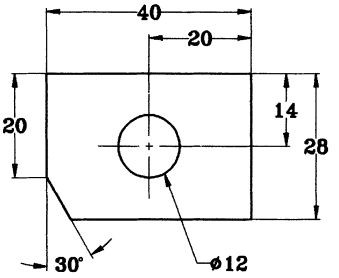

Figure 5.5 Application of dimensions.

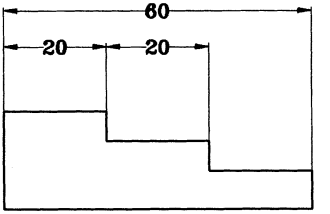

Figure 5.6 Grouping of dimensions.

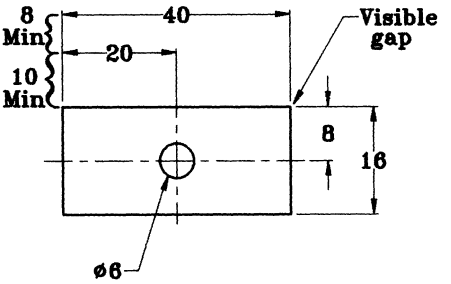

Figure 5.7 Spacing of dimensions.

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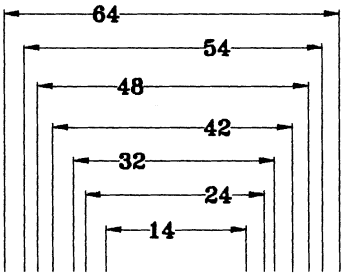

Figure 5.8 Staggered dimensions.

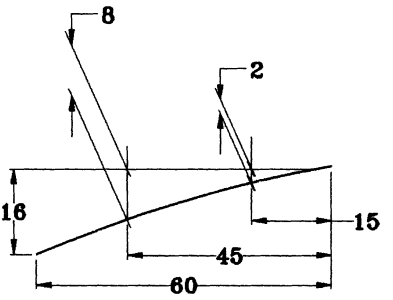

Figure 5.9 Oblique extension lines.

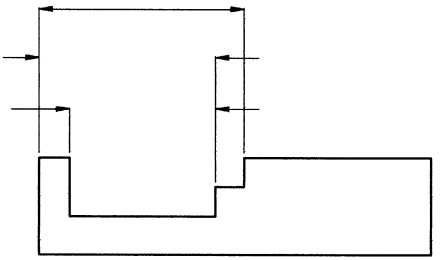

Figure 5.10 Breaks in dimension lines.

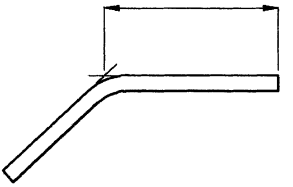

Figure 5.11 Point locations.

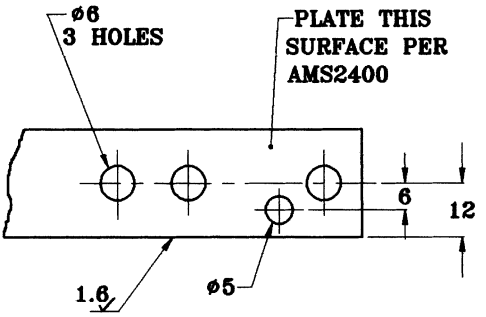

Figure 5.12 Leaders.

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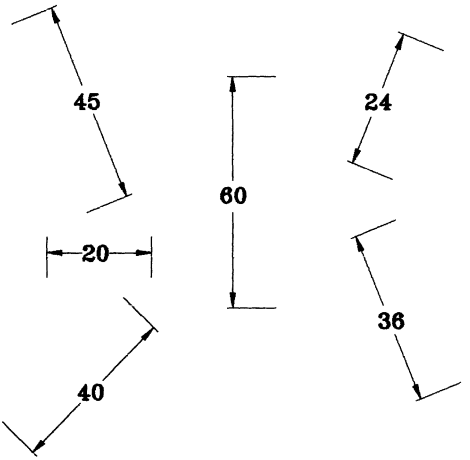

Figure 5.13 Reading directions of dimensions.

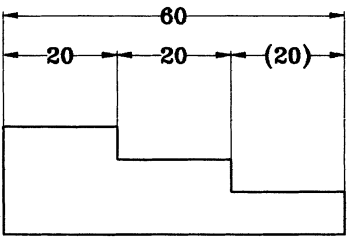

Figure 5.14 The intermediate reference dimension.

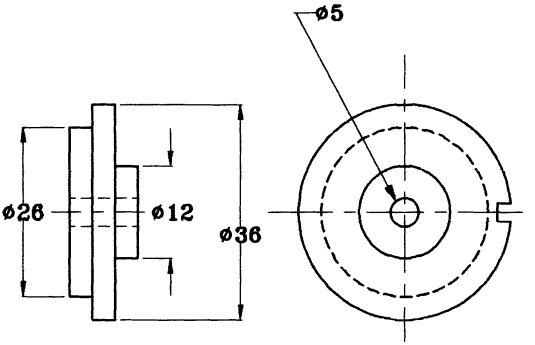

Figure 5.15 Dimensioning diameters.

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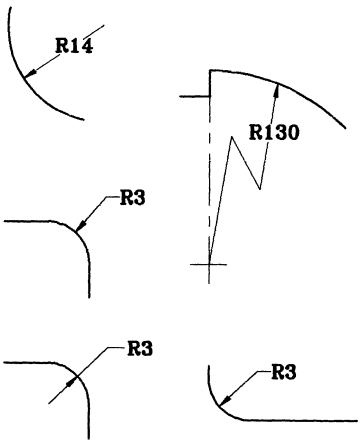


Figure 5.16 Dimensioning radii.

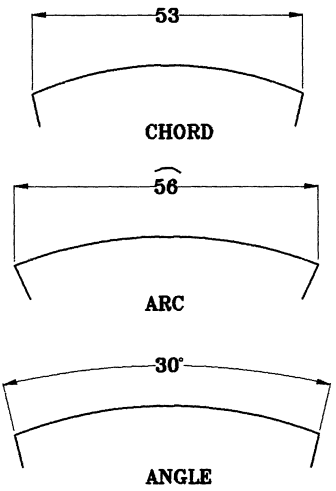
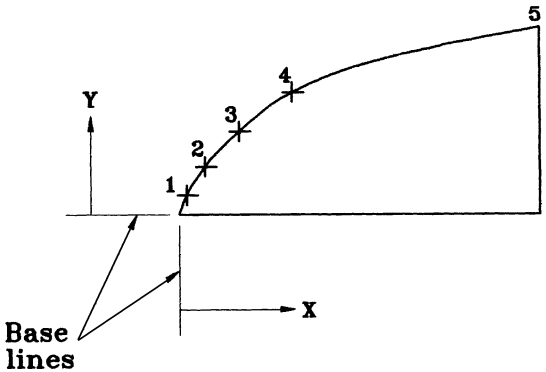


Figure 5.17 Dimensioning chords, arcs, and angles.



STATION	1	2	3	4	5
X	2	5	15	28	57
Y	4.3	8.5	14	19	24.5

Figure 5.18 Tabulated outline dimensions.

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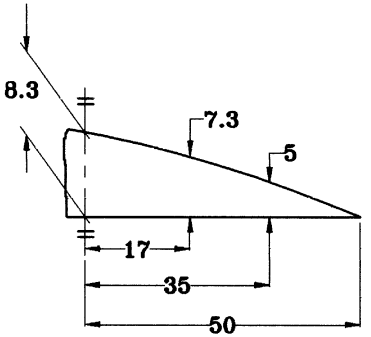

Figure 5.19 Symmetric outlines.

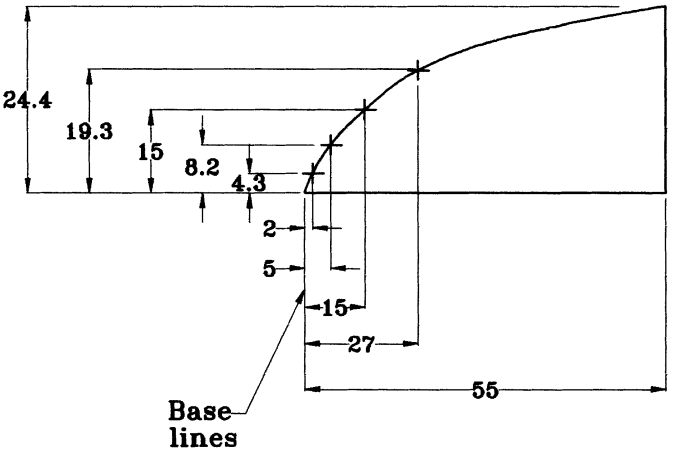

Figure 5.20 Coordinate or offset outline dimensions.

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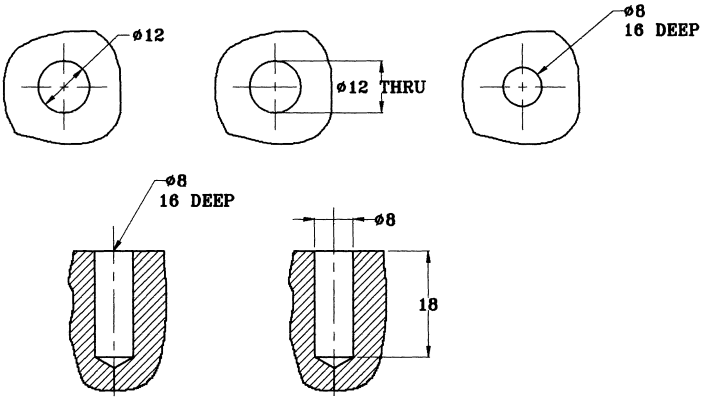

Figure 5.21 Dimensioning round holes.

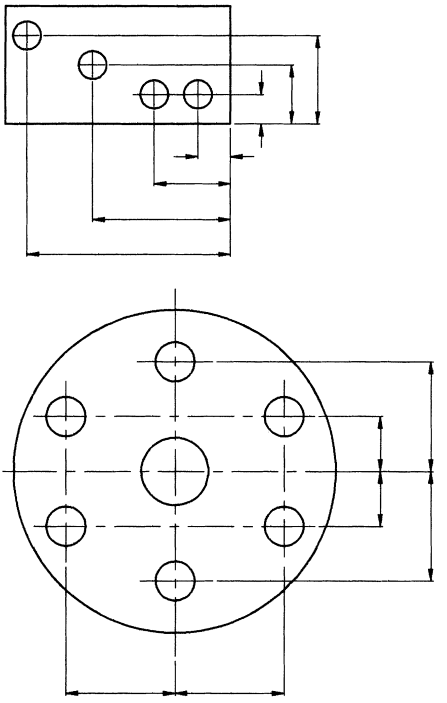

Figure 5.22 Rectangular coordinate dimensioning.

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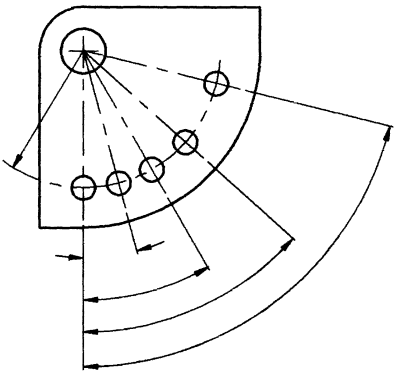

Figure 5.23 Polar coordinate dimensioning.

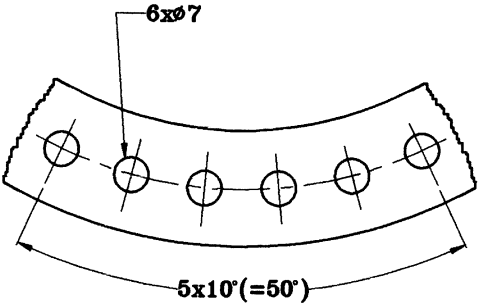

Figure 5.24 Dimensioning repetitive features.

5.1.4 ANSI Y14.5M-1994 (R1999) tolerancing practices

Per ANSI Y14.5M-1994 (R1999), tolerances may be expressed as follows:

- As direct limits or as tolerance values applied directly to a dimension
- As a geometric tolerance
- In a note referring to specific dimensions
- As specified in other documents referenced on the engineering drawing for specific features or processes
- In a general tolerance block referring to all dimensions on the engineering drawing, unless specified otherwise

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Tolerances on dimensions that locate features of size may be applied directly to the locating dimensions or specified by the positional tolerancing method. Unless otherwise specified, where a general tolerance note on a drawing includes angular tolerances, it applies to features shown at specified angles and at implied 90° angles, i.e., intersections of centerlines, corners of parts (internal and external), or other obvious areas not specifically shown to have angles other than 90°.

5.1.5 Direct tolerancing methods

Limits and directly applied tolerance values are specified as follows:

- *Limit dimensions.* The high limit or maximum value is placed above the low limit or minimum value. As a single-line callout, the low limit precedes the high limit, with a dash separating the values.
- *Plus and minus tolerancing.* The basic dimension is given first, followed by a plus-and-minus expression of tolerance.
- *Tolerance limits.* All tolerance limits are absolute.
- *Dimensional limits before or after plating.* For plated or coated parts, the engineering drawing or referenced document will state whether the dimensions are before or after plating; e.g., "Dimensional limits apply before plating" or "Dimensional limits apply after plating."

5.1.6 Positional tolerancing

Positional or *location tolerancing* defines a zone within which the center, axis, or center plane of a feature of size is permitted to vary from the true or exact position.

Geometric tolerancing is the general term applied to the category of tolerances used to control form, profile, orientation, location, and runout.

5.1.7 Examples of ANSI Y14.5M-1994 (1999) dimensioning and tolerancing practices

Figure 5.25 shows a typical engineering drawing using the ANSI form for dimensioning, tolerancing, and positioning. For a complete description and operational instructions for the use of ANSI standard dimensioning and tolerancing practices, see ANSI Y14.5M-1994 (1999), which may be obtained directly from ANSI, Inc. See Chap. 16

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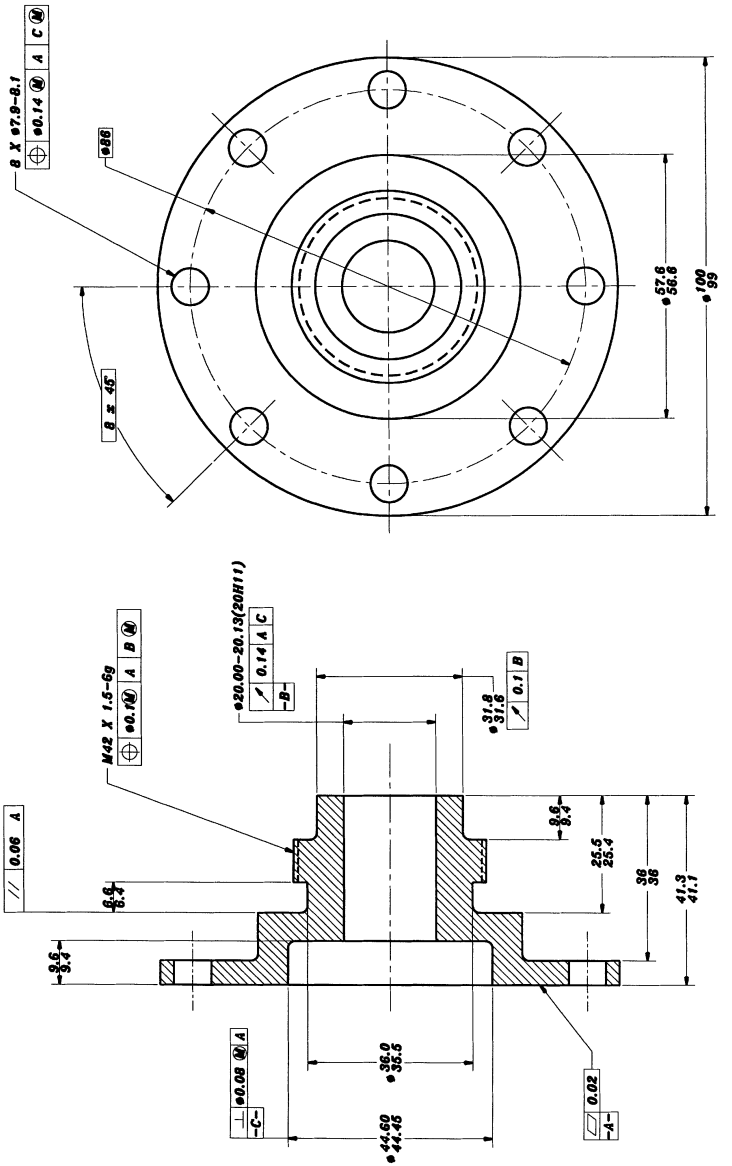

Figure 5.25 Feature control frame placement dimensions per ANSI Y14.5M-1994 (R1999).

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for addresses and acronyms of American standards organizations, specification authorities, societies, and institutes.

5.1.8 Design notes on dimensioning and tolerancing

From an electromechanical design standpoint, the dimensioning and tolerancing practices used on engineering drawings for the design and manufacturing of parts, subassemblies, and assemblies should take the following points into consideration:

- Close tolerances add cost to a finished product.
- The tolerance should be balanced to the function of the part.
- Arbitrary selection of a general tolerance can cause design and fit problems on the finished product or create unnecessary work.
- Use care in the selection of bilateral and unilateral tolerances.
- Remember that modern computer numerical controlled (CNC) turning centers, machining centers, electric discharge machining (EDM) machines, CNC punch presses, and other CNC equipment are capable of producing parts with closer tolerances than were possible in the past. Spindle accuracies are higher and CNC movement controls are very accurate on modern machine tools and equipment.
- Use tables of preferred limits and fits only when applicable.
- Select plating thickness limits (range) carefully so as to prevent dimensional interference between mating parts.
- To control a large tolerance spread owing to many parts in a dynamic assembly, design an adjustment means in the mechanism at one or more critical positions.
- Tooling fixtures and tooled parts help control tolerance ranges to a great extent on assemblies and complex mechanisms.
- Machined finishes are surface textures and therefore can be considered to have a tolerance [root-mean-square (rms)] value. Therefore, specify only a machined or tooled surface finish that is functional to the part.

The experienced electromechanical designer or product design engineer must be proficient in dimensioning and tolerancing practices to be most effective and successful at the design function. Many

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design and manufacturing problems occur when the engineering drawings are not dimensioned and toleranced properly and effectively. I therefore recommend that a thorough study be made of dimensioning and tolerancing practices through the use of ANSI YI4.5M-1982 (reaffirmed 1988) or a later revision.

5.1.9 Symbols used in ANSI Y14.5M-1994 (R1999) and ISO dimensioning and tolerancing

See Figure 5.26 for the ANSI and International Standards Organization (ISO) symbols currently used for dimensioning and tolerancing.

5.2 Typical Industrial Design Engineering Drawings

There are certain exceptions to the recommended dimensioning and tolerancing practices described in this chapter.

- Engineering drawings that are used exclusively within the confines of any particular company or organization may use drawing styles and dimensioning and tolerancing practices that differ from those shown in the preceding sections of this chapter. Some companies are still using the English fractional system of dimensioning, even though the fractional system was discontinued from general industrial use in the early 1950s.
- Different symbolisms for the different manufacturing processes such as welding, brazing, assembly, and so forth are also used by different companies.
- Tooling drawings such as that shown in Fig. 5.27 also may differ from the ANSI and ISO standards. Figure 5.27 shows a part that is to be die-stamped, and there are no tolerances on the drawing, with the exception of the hole location, which is produced at a different stage of manufacturing as a separate operation. The EDM machine that is used to cut the dies for this part will allow the part to be stamped exactly to the dimensions shown, i.e., to the precise three-place decimals indicated on the drawing.

Although there are exceptions to the modern dimensioning and tolerancing systems, as indicated previously, the advent of ANSI Y14.5M, SI, ISO 9000, and other national and international standards will make it difficult for American companies to compete in the

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SYMBOL FOR:	ANSI Y14.5	ISO
STRAIGHTNESS		
FLATNESS		
CIRCULARITY		
CYLINDRICITY		
PROFILE OF A LINE		
PROFILE OF SURFACE		
ALL AROUND PROFILE		NONE
ANGULARITY		
PERPENDICULARITY		
PARALLELISM		
POSITION		
CONCENTRICITY/COAXIALITY		
SYMMETRY	NONE	
CIRCULAR RUNOUT		
TOTAL RUNOUT		
AT MAXIMUM MATERIAL CONDITION	Ⓜ	Ⓜ
AT LEAST MATERIAL CONDITION	Ⓛ	NONE
REGARDLESS OF FEATURE SIZE	Ⓢ	NONE
PROJECTED TOLERANCE ZONE	Ⓟ	Ⓟ
DIAMETER	ø	ø
BASIC DIMENSION	50	50
REFERENCE DIMENSION	(50)	(50)
DATUM FEATURE	-A-	OR
DATUM TARGET		
TARGET POINT	X	X
DIMENSION ORIGIN		NONE
FEATURE CONTROL PLANE	⌖ø0.5Ⓜ A B C	⌖ø0.5Ⓜ A B C
CONICAL TAPER		
SLOPE		
COUTERBORE/SPOTFACE		NONE
COUNTERSINC		NONE
DEPTH/DEEP	↧	NONE
SQUARE (SHAPE)	□	□
DIMENSION NOT TO SCALE	15	15
NUMBER OF TIMES/PLACES	8X	8X
ARC LENGTH	105	NONE
RADIUS	R	R
SPHERICAL RADIUS	SR	NONE
SPHERICAL DIAMETER	Sø	NONE

Figure 5.26 ANSI and ISO dimensioning and tolerancing symbols.

world marketplace unless they adhere to these worldwide standards. One requirement of these systems is drawing, dimensioning, and tolerancing practices and engineering documentation control. Also, it is to be noted that when any particular company's engineering drawings are sent to outside vendors or subcontractors, these drawings

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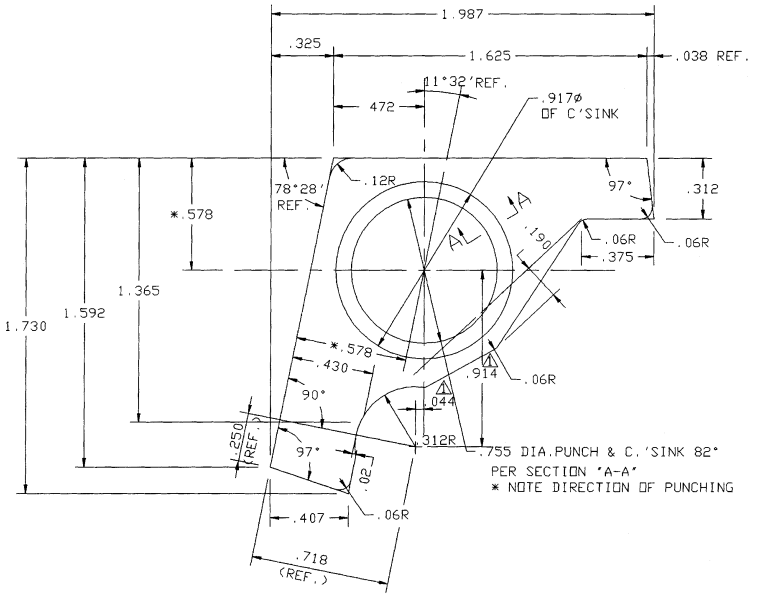

Figure 5.27 AutoCAD drawing showing typical industrial practice on a drawing for a tooled part.

always should be prepared to the national and international standards; otherwise, misinterpretations of the drawings may occur, causing losses, rejections, and possible lawsuits.

5.2.1 Limits and Fits, U.S. Customary and Metric Standards

Limits and fits of shafts and holes are important design and manufacturing considerations. Fits should be selected carefully according to function. The fits outlined in this section are all on a unilateral hole basis. Table 5.1 describes the various U.S. Customary fit designations. Classes RC9, LC10, and LC11 are described in the ANSI standards but are not included here. Table 5.1 is valid for sizes up to approximately 20 in in diameter and is in accordance with American, British, and Canadian recommendations.

The coefficients C listed in Table 5.2 are to be used with the equation $L = CD^{1/3}$, where L is the limit in thousandths of an inch corresponding to the coefficients C and the basic size D in inches.

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TABLE 5.1 U.S. Customary Fit Designations

Designation	Name and application
RC1	*Close sliding fits* are intended for accurate location of parts that must be assembled without perceptible play.
RC2	*Sliding fits* are intended for accurate location, but with greater maximum clearance than the RC1 fit.
RC3	*Precision running fits* are the loosest fits that can be expected to run freely. They are intended for precision work at slow speeds and light pressures, but are not suited for temperature differences.
RC4	*Close running fits* are intended for running fits on accurate machinery with moderate speeds and pressures. They exhibit minimum play.
RC5	*Medium running fits* are intended for higher running speeds or heavy journal pressures or both.
RC6	*Medium running fits* are for use where more play than RC5 is required.
RC7	*Free running fits* are for use where accuracy is not essential or where large temperature variations may occur or both.
RC8	*Loose running fits* are intended where wide commercial tolerances may be necessary, together with an allowance on the hole.
LC1 to LC9	*Locational clearance fits* are required for parts that are normally stationary but can be freely assembled and disassembled. Snug fits are for accuracy of location. Medium fits are for parts such as ball, race, and housing. The looser fastener fits are used where freedom of assembly is important.
LT1 to LT6	*Locational transitional fits* are a compromise between clearance and interference fits where accuracy of location is important, but either a small amount of clearance or interference is permitted.
LN1 to LN3	*Locational interference fits* are for accuracy of location and for parts requiring rigidity and alignment, with no special requirement for bore pressure. Not intended for parts that must transmit frictional loads to one another.
FN1	*Light drive fits* require light assembly pressures and produce permanent assemblies. Suitable for thin sections or long fits or in cast-iron external members.
FN2	*Medium drive fits* are for ordinary steel parts or shrink fits on light sections. They are the tightest fits that can be used with high-grade cast-iron external members.
FN3	*Heavy drive fits* are for heavier steel parts or for shrink fits in medium sections.
FN4 and FN5	*Force fits* are suitable for parts that can be highly stressed or for shrink fits where the heavy pressing forces required are not practical.

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The resulting calculated values of L are then summed algebraically to the basic shaft size to obtain the four limiting dimensions for the shaft and hole. The limits obtained by the preceding equation and Table 5.2 are very close approximations to the standards and are applicable in all cases except where exact conformance to the standards is required by specifications.

Example A "precision running fit" is required for a nominal 1.5000-in-diameter shaft (designated as an RC3 fit per Table 5.1).

Lower limit for the hole:	Upper limit for the hole:
$L_1 = CD^{1/3}/1000$	$L_2 = CD^{1/3}/1000$
$L_1 = 0\ (1.5)^{1/3}/1000$	$L_2 = +0.907\ (1.5)^{1/3}/1000$
$L_1 = 0$	$L_2 = 0.001038$
$d_L = 0 + 1.5000$	$d_U = 0.001038 + 1.5000$
$d_L = 1.50000$	$d_U = 1.50104$
Lower limit for the shaft:	Upper limit for the shaft:
$L_3 = CD^{1/3}/1000$	$L_4 = CD^{1/3}/1000$
$L_3 = -1.542\ (1.5)^{1/3}/1000$	$L_4 = -0.971\ (1.5)^{1/3}/1000$
$L_3 = -0.00176513$	$L_4 = -0.0011115$
$D_L = 1.500 + (-0.00176513)$	$D_U = 1.500 + (-0.0011115)$
$D_L = 1.49823$	$D_U = 1.49889$

Therefore, the hole and shaft limits are as follows:

$$\text{Hole size} = 1.50000/1.50104 \text{ diameter}$$

$$\text{Shaft size} = 1.49889/1.49823 \text{ diameter}$$

Table 5.3 shows the metric preferred fits for the cylindrical parts in holes. The procedures for calculating the limits of fit for the metric standards are shown in the ANSI standards. An alternative to this procedure would be to correlate the type of fit between the metric standard fits shown in Table 5.3 and the U.S. Customary fits shown in Table 5.1 and proceed to convert the metric measurements in millimeters to inches and then calculate the limits of fit according to the method shown in this section for the U.S. Customary system. The calculated answers then would be converted back to millimeters.

There should be no technical problem with this procedure except conflict with mandatory specifications, in which case you will need to concur with ANSI B4.2-1978(R1999) for the metric standard. The U.S. Customary standard for preferred limits and fits is ANSI B4.1-1967(R1999).

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TABLE 5.2 Coefficients *C*

	Hole limits		Shaft Limits	
Class of fit	Lower	Upper	Lower	Upper
RCI	0	+0.392	–0.588	–0.308
RC2	0	+0.571	–0.700	–0.308
RC3	0	+0.907	–1.542	–0.971
RC4	0	+1.413	–1.879	–0.971
RC5	0	+1.413	–2.840	–1.932
RC6	0	+2.278	–3.345	–1.932
RC7	0	+2.278	–4.631	–3.218
RC8	0	+3.570	–7.531	–5.253
LCI	0	+0.571	–0.392	0
LC2	0	+0.907	–0.571	0
LC3	0	+1.413	–0.907	0
LC4	0	+3.570	–2.278	0
LC5	0	+0.907	–0.879	–0.308
LC6	0	+2.278	–2.384	–0.971
LC7	0	+3.570	–4.211	–1.933
LC8	0	+3.570	–5.496	–3.218
LC9	0	+5.697	–8.823	–5.253
LT1	0	+0.907	–0.281	+0.290
LT2	0	+1.413	–0.442	+0.465
LT3*	0	+0.907	+0.083	+0.654
LT4*	0	+1.413	+0.083	+0.990
LT5	0	+0.907	+0.656	+1.227
LT6	0	+0.907	+0.656	+1.563
LN1	0	+0.571	+0.656	+1.048
LN2	0	+0.907	+0.994	+1.565
LN3	0	+0.907	+1.582	+2.153
FN1	0	+0.571	+1.660	+2.052
FN2	0	+0.907	+2.717	+3.288
FN3†	0	+0.907	+3.739	+4.310
FN4	0	+0.907	+5.440	+6.011
FN5	0	+1.413	+7.701	+8.608

Note: Coefficients are for use with the equation $L = CD^{1/3}$.

*Not for sizes under 0.24 in.

†Not for sizes under 0.95 in.

Source: J. Shigley and C. Mischke (eds.), *Standard Handbook of Machine Design.* New York: McGraw-Hill, 1996, p. 19.11.

The preceding procedures for limits and fits are mandatory practice for design engineers and tool design engineers in order for parts to function according to their intended design requirements. Assigning arbitrary or "rule of thumb" procedures for the fitting of cylindrical parts in holes is not good design practice and can create many problems in the finished product.

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TABLE 5.3 Metric Preferred Fits for Cylindrical Parts in Holes

Type	Hole basis	Shaft basis	Name and application
Clearance	H11/c11	C11/h11	*Loose running fit* is for wide commercial tolerances or allowances on external parts.
	H9/d9	D9/h9	*Free running fit* is not for use where accuracy is essential, but good for large temperature variations, high running speeds, or heavy journal pressures.
	H8/f7	F8/h7	*Close running fit* is for running on accurate machines and accurate location at moderate speeds and journal pressures.
	H7/g6	G7/h6	*Sliding fit* is not intended for running freely, but to move and turn freely and locate accurately.
	H7/h6	H7/h6	*Locational clearance fit* provides snug fit for locating stationary parts, but can be freely assembled and disassembled.
Transition	H7/k6	K7/h6	*Locational transition fit* is for accurate location, a compromise between clearance and interference.
	H7/n6	N7/h6	*Locational transition fit* is for more accurate location where greater interference is permitted.
Interference	H7/p6	P7/h6	*Locational interference fit* is for parts requiring rigidity and alignment with prime accuracy of location but with special bore pressures required.
	H7/s6	S7/h6	*Medium drive fit* is for ordinary steel parts or shrink fits on light sections, the tightest fit usable with cast iron.
	H7/u6	U7/h6	*Force fit* is suitable for parts that can be highly stressed or for shrink fits where the heavy pressing forces required are not practical.

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Source: McGraw-Hill Machining and Metalworking Handbook

Chapter

6

Computer-Aided Design, Manufacturing, and Engineering Systems

Regardless of what is being produced, the fabrication process nearly always begins with a computer-aided design drawing. While paper prints are still a necessity in some instances, the machining and metalworking industries have been transformed by the evolution of computer-aided design (CAD) and computer-aided manufacturing (CAM) systems. Two-dimensional drafting packages are largely giving way to three-dimensional solid-modeling packages. Although mechanical design typically is not the responsibility of the machinist or metalworker, machinists and metalworkers increasingly are required to be fluent in the use of a solid-modeling system for purposes of designing tooling, generating toolpaths, and conducting engineering analysis studies.

6.1 Computer-Aided Design (CAD)

6.1.1 File formats

Given the widely distributed nature of design and manufacturing, it is often the case that the machinist will not be working with the same CAD package as the mechanical designer. In these cases, either the machinist's CAD system must be capable of importing the CAD format used by the mechanical designer, or the two must agree on a neutral interchange format.

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Some of the more commonly encountered CAD file formats can be found in Table 6.1. Of the formats shown on this list, IGES and STEP are examples of neutral data-exchange file formats developed by standards committees. The Parasolid and ACIS formats are commercial formats, but they are also of interest in the sense that most of the CAD systems represented in Table 6.1 are built on either the Parasolid or the ACIS kernel. If the mechanical designer and machinist both happen to use CAD systems built on the same kernel, then they typically have the option of swapping files using either the Parasolid or the ACIS file formats. Having said this, many CAD vendors have built import-export support for competitors' file formats into their systems as a matter of corporate strategy. Having the ability to import files from a competing system makes it easier for a company to switch CAD systems without having to redesign all of its CAD models. Support for multiple file formats also facilitates file transfers between design firms and the array of external suppliers manufacturing the components or subsystems.

It is worth noting that when a CAD file is imported from a different system, the workpiece geometry typically is the only information that gets transferred. Embedded notes, tolerances, and other types

TABLE 6.1 Commonly Used CAD File Formats

CAD system or standard	Associated file format(s)
ACIS	*.SAT
AutoCAD	*.DWG; *.DXF
Autodesk Inventor	*.IPT
CADKEY	*.PRT
CATIA	*.CGR
IGES	*.IGS; *.IGES
Parasolid	*.X_B; *.XMT_BIN (binary files) *.X_T; *.XMT_TXT (text files)
ProEngineer	*.PRT; *.ASM
SolidEdge	*.PAR; *.ASM
SolidWorks	*.SLDPRT; *.SLDASM; *.SLDDRW
STEP	*.STP; *.STEP
STL	*.STL
Unigraphics	*.PRT
VRML	*.WRL

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of nongeometric information often are lost when a CAD model is ported into another file format. Models consisting of complex surfaces that have been stitched or otherwise blended together do not always transfer cleanly between systems either.

6.1.2 CAD vendors

There are numerous suppliers of CAD software throughout the United States and other countries. A list of these software suppliers is shown in Table 6.2.

6.1.3 CAD terminology

As mentioned previously, the machinist or metalworker often is called on to design molds, dies, and/or machining fixtures that are needed to fabricate a given part. Although it is well beyond the scope of this *Handbook* to describe how tools, dies, etc. are designed in a given CAD system, it is worthwhile to outline the basic terminology associated with these systems, as well as the general approaches that may be employed by machinists and metalworkers.

Feature-based design. This refers to the act of designing parts by successively adding one solid feature after another. The features may either add volume to the model (i.e., an additive feature) or remove volume from the model (i.e., a subtractive feature). Examples of features include holes, slots, chamfers, fillets, shells, etc.

Parametric CAD. The size and location of each feature in the CAD system is defined by parameters (e.g., length, width, etc.). The solid

TABLE 6.2 Selected CAD Vendors

Company	Web site	Product(s)
Autodesk, Inc.	*www.autodesk.com*	AutoCAD Inventor
Bentley Systems, Inc.	*www.bentley.com*	Microstation
Dassault Systems	*www.3ds.com*	Catia
Parametric Technology Corp.	*www.ptc.com*	Pro/Engineer
Solidworks Corp.	*www.solidworks.com*	SolidWorks
TurboCAD	*www.turbocad.com*	TurboCAD
UGS	*www.ugs.com*	NX
	www.solidedge.com	Solid Edge

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features will change size, shape, and/or location depending on the values that you assign to the parameters. If you increase the value of length parameter for a cube, the distance between the two end faces will increase accordingly. More important, if you have specified the distance of a hole from one end of the cube, then it will remain at that distance regardless of how long or short the cube is. The CAD modeler need not worry about repositioning every feature if the size of the cube changes.

Parametric associativity. This is among the most important aspects of modern CAD systems. It means that you can link, or associate, the size and/or position of a feature in one CAD model with the size and/or location of a feature in another CAD model. Suppose a machining fixture has been modeled that consists of a steel plate with a number of drill bushings. The steel plate will have holes machined in it that correspond to the locations of the drill bushings. Likewise, the size of the holes must be related to the outer diameter (OD) of the drill bushings. It is possible to link the hole diameter in the steel plate's CAD model with the OD of the drill bushing. If a different-diameter drill bushing is selected, then the associated hole diameter in the steel plate will change automatically when the CAD model is rebuilt. Associativity can go far beyond this simple example. The dimensions on a part drawing will update automatically when the solid model for that part changes. Toolpaths generated in CAM packages can be associated with CAD model geometry. If the curvature on a mold surface is modified slightly by the designer, then a parametrically associated CAM system will automatically regenerate its toolpaths accordingly.

Assembly layout sketch. This is a sketch that shows the overall size and location of parts within an assembly.

Top-down design. With top-down modeling, the designer will generate assembly layout sketches in an assembly file that shows key dimensions, shapes, and locations of components in the assembly. Then the individual components are modeled with their vertices, edges, and faces referring back to the sketches in the top-level assembly file. Any time the modeler changes the assembly layout drawing, the components that are linked to the layout sketch update automatically. In other words, the design starts with the assembly and then proceeds to the individual parts.

Bottom-up design. With bottom-up modeling, each individual component is modeled first. The components are then brought together in

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an assembly file. Of course, it is possible to mix the two approaches as well.

6.1.4 Solid modeling techniques

Creating base features. The process of modeling an individual component typically begins with a two-dimensional sketch. This sketch may be extruded linearly, revolved, or swept along a guide path to create a three-dimensional *base feature*. Figure 6.1 shows how the same rectangular sketch can be extruded, revolved, or swept to produce completely different base features.

To put these three approaches in the context of activities that might be performed by a machinist, the linear extrude would be used to model the basic shape of a rectangular mold base. The revolve would be used to model cylindrical components such as ejector pins. The sweep could be used to model a U-shaped path followed by a cooling channel.

Once a base feature is created, additional features can be created by making new sketches that are extruded, revolved, or swept. These subsequent features can be used to add volume to the existing part, or they can be used to cut material away from an existing part. Figure 6.2*a* and *b* show how an extruded circle can be used to create a hole or a boss depending on whether the CAD modeler specifies an additive or subtractive feature. In both cases, a circle was sketched on the front face of the plate. The circle was extruded away from the plate in Fig. 6.2*a* to add a boss. The circle was cut-extruded into the plate in Fig. 6.2*b* to create a hole.

When creating a feature from a sketch, the following procedure is generally followed:

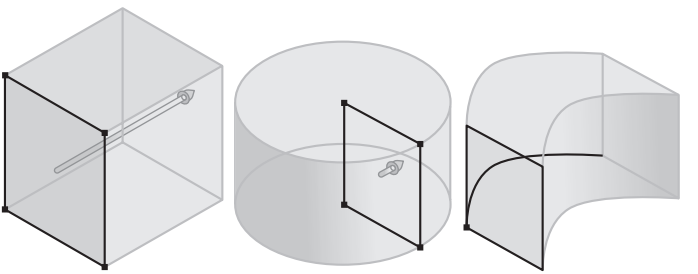

Figure 6.1 (*a*) Extruded rectangle. (*b*) Revolved rectangle. (*c*) Swept rectangle.

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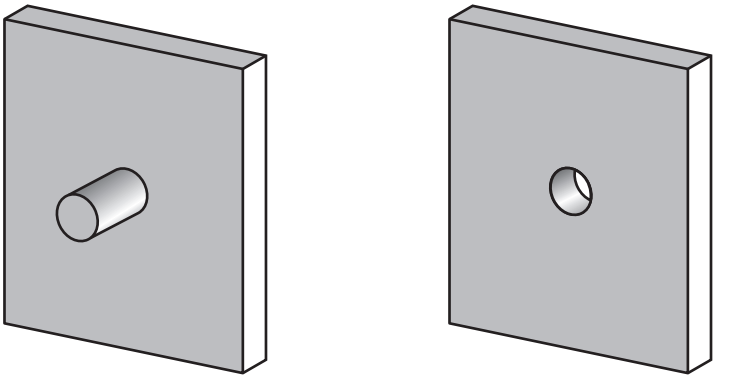

Figure 6.2 (*a*) Additive feature. (*b*) Subtractive feature.

- Quickly sketch the desired shape using lines, arcs, circles, splines, etc. Just sketch the approximate shape, and do not be concerned with whether the sketch entities are the correct size.
- Apply geometric relationships that constrain the size and/or location of the sketched entities.
- Apply dimensions.
- Extrude, revolve, or sweep the sketch to add or subtract volume from the model.

Capturing the design intent. Many CAD modelers fail to appreciate how important it is to use good practices when assigning geometric relationships and dimensions to a sketch. The term *design intent* is used frequently in connection with these steps. When an individual models the "design intent," he or she is creating the model such that the model will update properly when the inevitable design changes are made. In a sense, the modeler also should make the models as error-proof as possible. This is important because it is quite possible that other individuals not familiar with the model may be required to modify it at a future time.

One of the simplest ways to model the design intent and to make a model as error-proof as possible is to specify geometric relations wherever possible instead of explicitly defining dimensions. Table 6.3 shows different types of sketch relationships that are commonly available in most solid-modeling CAD systems.

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TABLE 6.3 Geometric Relationships

Type of relationship	Description
Coincident	The selected sketch point lies on a line or arc.
Collinear	A pair of selected lines lies on the same infinite line.
Concentric	A pair of selected arcs has the same center point.
Coradial	A pair of selected arcs has the same center point and radius value.
Equal	The selected entities have the same length or radius value.
Horizontal	The selected entities (points, lines) are aligned horizontally with respect to the coordinate system.
Perpendicular	The selected lines are oriented 90° to one another.
Parallel	The selected lines are parallel with each other.
Tangent	The selected line is tangent to the selected circle or arc.
Vertical	The selected entities (points, lines) are aligned vertically with respect to the coordinate system.

Example: Consider the mold insert plate shown in Fig. 6.3. The plate has a hole on each of the four corners. Suppose that the intent is for all four of these holes to be 0.250 in in diameter, 0.500 in deep, and 0.375 in from each of the two edges that bound the corner they are closest to. Because these four holes lie on the same plane, they can be created with a single sketch containing four circles. One approach to constraining this sketch would be to apply a 0.250-in-diameter dimension to each of the four holes. Then the vertical and horizontal distance of 0.375 in from each hole to the edges it is closest to could be specified (i.e., eight distance dimensions for the four holes). Now suppose that the size of the hole changes from 0.250 to 0.375 in. The modeler will have to go back and explicitly change the diameter dimension for every one of the four holes. Suppose that the 0.375-in side offset changes to 0.4063 in. The modeler will have to go back and change all eight distance dimensions.

A much more efficient way of specifying the design intent for this plate would be to apply the following relations:

- Apply an *equal diameter* relation to holes 1, 2, 3, and 4.
- Apply a *horizontal* relation to holes 1 and 2.
- Apply a *horizontal* relation to holes 3 and 4.
- Apply a *vertical* relation to holes 1 and 3.

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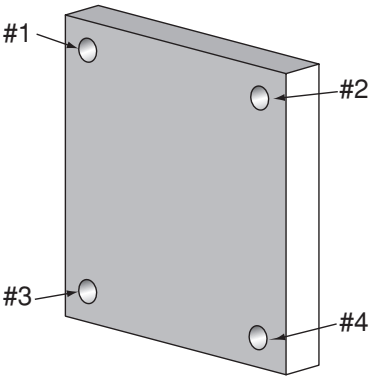

Figure 6.3 CAD model of plate with four holes.

- Apply a *vertical* relation to holes 2 and 4.
- Apply an *equal* relation that says the distance of hole 1 from the left edge is equal to the distance of hole 1 to the top edge.
- Apply an *equal* relation that says the distance of hole 1 from the top edge is equal to the distance of hole 4 to the bottom edge.
- Apply an *equal* relation that says the distance of hole 1 from the left edge is equal to the distance of hole 4 to the right edge.

If the size of hole 1 is now dimensioned to 0.250 in, then the diameter of the other three holes will change automatically to match that of hole 1. If the 0.375-in distance of hole 1 from the left edge then is dimensioned, all four holes will be located automatically the appropriate distance from their edges by virtue of the relations. If the hole diameters need to be changed for any reason, the modeler simply changes a single diameter (hole 1), and the rest of the holes will update automatically. Likewise, if the offset distance from the holes to the edge of the plate changes, the modeler simply has to change a single dimension rather than the eight dimensions using the previously described modeling approach. This is a very simple example that dramatically illustrates how important proper modeling technique can be. Without these parametric relationships, it is very easy to make mistakes when design changes are made. If these mistakes go unnoticed all the way to the shop floor (and they often do), then the consequences can be quite costly.

Using predefined features. In addition to creating new geometry using extruded/revolved/swept features, CAD systems also make available libraries of the most commonly used features. Predefined features made available typically include

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Generic features

- Holes (through, blind, countersunk, counterbored, etc.)
- Threads
- Fillets
- Chamfers
- Shells (hollowed solids with a defined wall thickness)
- Arrays (circular, rectangular)

Sheet metal features

- Flanges
- Lances
- Louvers
- Ribs
- Hems

Other helpful modeling tips

Establish overall shape first. Start any model with a base feature that defines the overall size and shape of the component. Then add those features that establish how this component will be assembled with other components. Small features, such as chamfers, fillets, and threads, may serve an important role in the mechanical functioning of a part, but they generally should be added last in a model.

Mirror symmetric features. When a component has symmetric features on its left/right, top/bottom, or front/back directions, then model a feature once and mirror it about a midplane to the other side. The obvious advantage is that it saves a tremendous amount of modeling time. It also makes the model more error-proof because the geometry on the mirrored side is linked to the geometry of the originating feature. Likewise, the size of the CAD model will be reduced because the feature is not included twice.

Use feature arrays. If multiple instances of a feature are needed in a systematic pattern, then create a linear or circular array from one base feature rather than creating the feature multiple times. This is faster and generally will result in smaller file sizes.

Create your own feature libraries. Tool and die design is a repetitive process. The same geometric shapes often are modeled repeatedly,

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perhaps with slight variations in overall size and the presence or absence of certain features. These geometric shapes should be developed parametrically and then filed away as custom reusable features. For instance, louvers are used widely in sheet metal fabrication, yet the width, depth, and bottom fillet radius will vary considerably from one part to the next. In this case, a single louver should be modeled with three basic parameters—*width, depth, and bottom_fillet_radius.* File the feature away, and then reuse it when needed simply by changing any or all three of the parameters.

Use meaningful parameter names. When you create a feature, the CAD system has no notion of what the feature is. It therefore will create a default name for each newly created parameter such as *D1, D2,* etc. It is good practice to rename all parameters that are critical to the basic function and understanding of the model. When someone else examines your model and sees parameter names of *width, depth,* and *bottom_fillet_radius,* then he or she likely will have much better luck figuring out how to edit/update the model than if the parameter names were *D1, D2,* and *D3,* respectively.

6.1.5 Standard part/assembly libraries

One of the most significant advances in CAD solid modeling as far as the machinist or metalworker is concerned is the emergence of standard part and assembly libraries. In many instances, CAD models for standard tooling components are available free of charge from the manufacturer or its distributor via Internet download. For example, CAD models from over 200 manufacturers can be found by searching the available catalogs of the Part Solutions Web site at *www.part-solutions.com.* The available catalogs encompass mold and die systems, workholding systems, national/international standards, and more. These vendor-supplied CAD models are tremendous time savers, and they often can reduce the occurrence of manufacturing errors.

In some cases, add-in programs are available for a fee. These programs embed themselves within a given CAD system as an additional menu option. They often have more functionality than just providing the machinist or metalworker with a library of parts to choose from. Some of them offer so-called design wizards that help streamline the mechanical design process.

Table 6.4 lists selected companies that provide products or services related to mechanical component libraries for items such as fasteners, gears, bearings, sprockets, etc. In some cases, these com-

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TABLE 6.4 Selected CAD Component Library Providers

Company	URL	Related product(s)
Alamar Systems	*www.edgeparts.com*	ASAP
BCT Technology AG	*www.bct-technology.com*	3D Pool
Bogner and Herac GmbH	*www.solidedge.at*	ISL
Cadalog, Inc.	*www.cadalog-inc.com*	SE-PartsXL
CADBAS, GmbH	*www.cadbas.de*	CADBAS-PartExplorer
CADENAS	*www.cadenas.de*	PARTsolutions
CAD-Partner	*www.cadpartner.de*	CAD-Partner
CadParts, Inc	*www.cadparts.com*	Fastener Library
Camnetics, Inc.	*www.camnetics.com*	GearTrax and CAMTrax
Engineering S.P.A.	*www.engineering.it*	Standard Parts
Ideal Industrial	*www.ideal-parts.com*	IDEAL-PARTS
ISAP AG	*www.isap.de*	Part Manager
Jacobs Associates, LLC	*www.jacobsassociates.com*	Jacobs Professional Productivity Suite
Logopress	*www.logopress3.com*	123Go
Modularis Software AG	*www.starvars.de*	CAD-Symbols
PARTsolutions LLC	*www.part-solutions.com*	PARTSolutions
Scibit	*www.scibit.com*	Scibit
SolidLib.com Corp.	*www.solidlib.com*	SolidLib.com
SolidPartners, Inc.	*www.solidpartners.com*	SolidParts
Solidworks Corp.	*www.solidworks.com*	Solidworks Toolbox
Stream Design ApS	*www.stream-design.com*	Systems/Parts
TDS	*www.tds-technik.cz/en/*	TDS-Technical
Teamworks GmbH	*www.pwnorm.de*	PowerWorks Norm
TRACE PARTS	*www.traceparts.com*	Trace Parts
Web2CAD AG	*www.web2cad.com*	PowerParts

panies provide libraries that are based on an applicable standard (ANSI, DIN, etc.). Other vendors provide libraries of parts based on actual components supplied by manufacturers.

6.1.6 Designing sheet metal flat patterns

Much of the preceding discussion of CAD modeling techniques was generic in nature. However, modern CAD systems have advanced considerably the ease with which sheet metal components and their associated tooling are designed. Chapter 9 discusses analytic methods for determining factors such as setbacks and bend radii in relation to the composition and thickness of the sheet being used.

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Modern CAD systems now have much of this expertise built in. In some cases, sheet metal capabilities are built into the CAD system. In other cases, optional sheet metal modules include databases for a wide variety of materials and thicknesses.

The sheet metal modules present in CAD systems work by providing the designer with built-in features that are specific to sheet metal (flanges, louvers, relief cuts, etc.). Because the CAD system recognizes each bend and cut as a sheet metal feature, it is able to "flatten" the sheet metal part into the flat pattern that must be cut from a sheet to produce the part blank. Flat patterns for one or more parts are then imported into special nesting programs that nest parts as tightly as possible on a given sheet in order to maximize material utilization. This nested pattern then can be fed to a laser cutting machine.

An example can be seen in Fig. 6.4. This figure shows a boxlike sheet metal part with bends, mitered flanges, a cut through a flange, and louvers. The part was modeled in the SolidWorks CAD system using built-in sheet metal features. For example, the miter flange feature creates all three flanges on the rear side of the part along with the respective miters. The user merely clicks on the edge(s) to receive a flange, specifies the flange length, and accepts or edits the default bend radius. SolidWorks then automatically creates all three flanges along with their miters. Likewise, the louvers are built-in parametric features. The user drags and drops a louver on the desired face, positions and orients it, and then specifies the dimensions. SolidWorks then automatically constructs the solid louver features. The sheet metal module includes default tables for bend factors, and those tables can be customized by the user. Figure 6.5 shows the box in its flat-pattern state. This is accomplished with a single click of the mouse button. Note that the bend lines are shown as well.

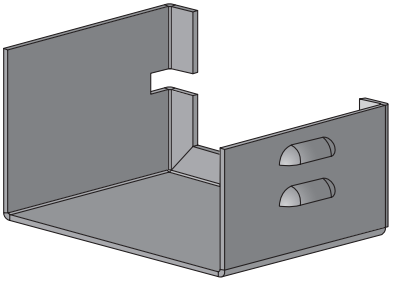

Figure 6.4 Folded sheet metal example.

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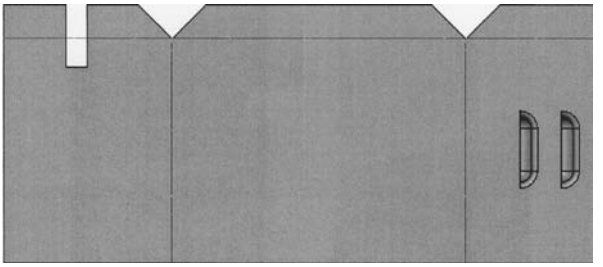

Figure 6.5 Flattened sheet metal example.

6.2 Computer-Aided Manufacturing (CAM)

In most cases, the term *computer-aided manufacturing* refers to the process of semiautomatically generating computer numerical control (CNC) machine toolpaths from a CAD model. In reality, CAM packages encompass a much broader range of activities. For example, the increasing use of laser and waterjet systems to cut sheet and plate materials has led to new developments in nesting software. These systems nest patterns on a sheet of specified size such that the largest number of parts can be cut from the smallest amount of material.

When selecting a CAM package for CNC machining, it is necessary to consider many different factors:

- *Stand-alone versus integrated CAD.* Most CAM systems are available in a stand-alone version. Some are also available as add-ons to a particular CAD system (i.e., they appear as an extra menu item in the CAD system). If toolpaths are to be generated from a mix of different CAD systems, then there may not be much advantage to using an integrated CAM system. If, however, virtually all toolpaths will be generated from the same CAD system, then it is definitely an option to consider. A valuable advantage of integrated CAD/CAM is toolpath associativity. As mentioned previously, this is where toolpaths are updated automatically when changes to a part's geometry are made. It is also the case that CAD models often are built using predefined features such as holes, slots, etc. Modern CAM systems have intelligent machining wizards that attempt to semiautomatically recognize machining features in a part. For instance, they might recognize a pocket and then attempt to semiautomatically generate roughing and finishing operations using appropriate end mills. For some types of parts, this can result in significant time savings.

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- *Network licensing.* For large companies that purchase many sets of a CAM package, it is usually much simpler for the information technology (IT) department to install the software once along with a floating network license. For smaller installations, support for network licensing is less important.
- *Number of simultaneous axes.* CNC machines are configured most often with three, four, or five axes of motion. Not all CAM packages support fourth- or fifth-axis commands. Some CAM packages do support commands for fourth and possibly fifth axes, but they do not allow *simultaneous* four- or five-axis motion. If true simultaneous four- or five-axis motion is needed for a machine, then the CAM vendor should be asked to clarify if this is supported.
- *Types of processes supported.* Some CAM packages can generate paths for other types of processes such as wire or sinker electric discharge machining (EDM) machines, waterjet cutters, etc.
- *Availability of postprocessors.* G code is not as standard as it might appear, particularly when four- or five-axis motion is involved. Different machine controllers expect part programs to be formatted in different ways, and not all G or M codes are supported by every controller. Consequently, CAM systems must "post" (postprocess) their toolpaths to match the specific machine the code will be run on. The reseller should be asked whether or not the necessary postprocessors are available and whether or not there is an extra charge for them. If they are not available, the reseller should be asked how much it would cost to write the new post.
- *Technical support and training.* Learning a new CAM system is not always easy, particularly when four- or five-axis motion is involved. Although the market share of a CAM system should not be a primary factor in selecting a system, it can provide an indicator of how easy or difficult it will be to hire trained CAM operators. The larger the user community is for any system, the more resources generally are available, such as third-party training manuals and short courses, online user groups, etc.
- *File import-export capability.* For obvious reasons, it is important to verify that the CAM package supports the CAD file format(s) of interest.
- *Graphic toolpath verification.* Graphic toolpath verification refers to software that simulates the part program on the computer display. The raw stock for the workpiece is modeled along with (optionally) any workholding devices. The program then

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graphically displays material being removed from the part blank as the cutting tool progresses through the part program. Toolpath verification is a very inexpensive way to discover programming errors. The alternative of discovering a toolpath error on the machine can be catastrophic. Not all CAM systems provide graphic toolpath verification, and some only provide it as an extra option. It is important to clarify whether or not this feature is provided when a CAM system is purchased.

- *Tool and material databases.* Many CAM programs come equipped with user-customizable cutting tool and material databases. For any given machining operation, the user specifies the specific alloy being machined, as well as the type of cutting tool used. The CAM program will then apply default cutting parameters from its database. The material and machining parameter databases typically can be edited by the user. This allows users to add new materials or to enter machining parameters recommended by the manufacturing of the cutting tools in use.

Table 6.5 provides a listing of selected CAM software vendors, their Web sites, and related product offerings.

6.2.1 CNC part programming fundamentals

A *part program* is the text file that contains machining instructions for the CNC machine to produce a particular part. Whether a part program is generated via a CAM package or is written manually using a text editor, it must adhere to the syntax and format for the machine on which it will be run. ISO 6983-1:1982 and ANSI/EIA RS-274-D are standards that define the syntax for numerical control of machines. While the vast majority of machine tool makers have adopted these standards, a small number of machine tool makers use their own propriety standards.

In order to write or read a part program, it is necessary to understand some fundamental concepts and terminology.

G codes These are codes that instruct the cutting tool to move to the specified location in the prescribed manner (linear, circular, etc.). Selected G codes for CNC milling are shown in Table 6.6. Selected G codes for CNC turning are shown in Table 6.7.

M codes These are miscellaneous codes that instruct the machine to perform nonmovement actions such as turning on/off the coolant. Selected M codes for CNC milling are shown in Table 6.6. Selected M codes for CNC turning are shown in Table 6.7.

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TABLE 6.5 Selected CAM Vendors

Company	URL	Related product(s)
AccuMetria	*www.agile.com*	CMMWorks
Advanced Tubular Technologies	*www.advancedtubular.com*	Benderlink
Anderson CAD/CAM, Inc	*www.acadcam.com*	GeoWORKS
Antech Micro Systems	*www.antechmicro.com*	CADlink
Applied Production	*www.appliedproduction.com*	ProFab Series
AUTON srl	*www.auton.it*	AUTON Cam Processor
CamSoft Corp.	*www.camsoftcorp.com*	Advanced System 3000
Camtek, Ltd.	*www.peps.com*	PEPS SolidCut
CN Industries	*www.cn-industries.com*	Goélan V4
CNC Software, Inc.	*www.mastercam.com*	MasterCAM
COSCOM Computer	*www.millit.com*	Millit
Delcam International	*www.delcam.com*	PowerMILL
DP Technology Corp.	*www.dptechnology.com*	ESPRIT
EFICAD	*www.eficad.fr*	EFICN SW
EMBLEM Corp.	*www.emblem.co.jp*	PowerEdge/Mill
Engineering Geometry Systems	*www.featurecam.com*	FeatureCAM
FeatureCAM/Engineering Geometry Systems	*www.featurecam.com*	FeatureCAM
Gibbs and Associates	*www.GibbsCAM.com*	GibbsCAM
IMAO Corp.	*www.imao.co.jp*	IMAO CAD/CAF
IMCS, Inc./PartMaker	*www.partmaker.com*	PartMaker
Jetcam International Holding, Ltd.	*www.jetcam.com*	JETCAM Expert Systems
Licom Systems	*www.licom.com*	AlphaCAM
MecSoft Corp.	*www.mecsoft.com*	VisualMill
NCCS	*www.nccs.com*	NCL

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Opus	*www.opus-cam.de*	OPUS CAM
Pathtrace Engineering Systems	*www.edgecamforsolidworks.com*	EdgeCAM
QARM Pty, Ltd.	*www.onecnc.com*	OneCNC
SolidCAM, Ltd.	*www.solidcam.com*	SolidCAM
SPRUT Technology	*www.sprutcam.com*	SprutCAM
Surfware, Inc.	*www.surfware.com*	SURFCAM
TekSoft CAD/CAM System, Inc.	*www.teksoft.com*	CAMWorks, ProCAM
UGS	*www.ugs.com*	NX Machining
Vero International Software UL	*www.vero-software.com*	VISI-Series
Vision Numeric	*www.type3.com*	Type3
Wittlock Engineering	*www.wittlockeng.com*	WE-CIM

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TABLE 6.6 Selected CNC Milling G Codes and M Codes

G Code	Description	M Code	Description
G00	Rapid positioning	M00	Program stop
G01	Linear interpolation	M02	Program end
G02	Clockwise circular interpolation	M03	Spindle on clockwise
G03	Counter clockwise circular interpolation	M04	Spindle on counter clockwise
G04	Dwell	M05	Spindle stop
G40	Cancel cutter compensation	M06	Tool change
G41	Left cutter compensation	M08	Coolant on
G42	Right cutter compensation	M09	Coolant off
G43	Tool length compensation	M30	End program and reset to start
G44	Cancel tool length compensation		
G45	Increase tool offset		
G46	Decrease tool offset		
G70	Inch units		
G71	Metric units		
G81	Drilling cycle		
G90	Absolute positioning		
G91	Incremental positioning		

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TABLE 6.7 Selected CNC Turning G Codes and M Codes

G Code	Description	M Code	Description
G00	Rapid positioning	M00	Program stop
G01	Linear interpolation	M02	Program end
G02	Clockwise circular interpolation	M03	Spindle on clockwise
G03	Counter clockwise circular interpolation	M04	Spindle on counter clockwise
G04	Dwell	M05	Spindle stop
G20	Inch units	M06	Tool change
G21	Metric units	M08	Coolant on
G40	Cancel tool nose radius compensation	M09	Coolant off
G41	Left tool nose radius compensation	M30	End program and reset to start
G42	Right tool nose radius compensation		
G70	Finishing cycle		
G71	Turning cycle		
G72	Facing cycle		
G76	Threading cycle		
G90	Absolute positioning		
G91	Incremental positioning		

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Absolute versus incremental positioning G codes that govern motion of the cutting tool determine the (*x, y, z*) coordinates of the cutting tool at the end of the move. If a G90 code is specified at the start of the part program, then any (*x, y, z*) coordinates specified in the program are absolute locations relative to the machine's (0, 0, 0) position. If a G91 code is specified at the start of the part program, then any (*x, y, z*) coordinates specified in the program are distances relative to where the cutting tool was at the start of the command.

x,y,z These are the values that specify the desired location for the cutting tool at the end of the move.

i, j, k These are (*x, y, z*) coordinates for the center of an arc during a move.

S This is the spindle speed in revolutions per minute.

F This is the feed rate in inches per minute or millimeters per minute.

T This is the tool number to load during a tool change command.

N Line number.

Sample part programming commands for milling

```
%
:0526                    (Program 0526)
N10 G90 G70              (Absolute coordinates, units in inches)
N20 M06 T6               (Load tool 6 from the tool changer into
                          the spindle)
N30 M03 S1000            (Turn spindle on CW at 1000 rev/min)
N40 G00 X2 Y0            (Rapid move to absolute x = 2, y = 0)
N50 G01 Z1 F30           (Linear move to z = 1 at 30 in/min)
N60 G01 Z-0.125 F10      (Linear feed to Z = –0.125 at 10 in/min)
N70 G02 X-2 Y0 I0 J0     (Cut CW arc from starting point of x = 2,
                          y = 0. To x = –2, y = 0, with the center
                          at x = 0, y = 0)
N80 G00 Z1               (Rapid move up to Z = 1)
N90 M05                  (Turn off the spindle)
N100 M30                 (Program stop)
```

6.2.2 CAM toolpath generation procedure

Although the details and terminology vary with every CAM system, the basic steps are fairly similar in most cases. The first step is to

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import the workpiece geometry. If the part is to be held in place with toggle clamps or other fixturing devices in the general vicinity of the cutting tool, then it's a good idea to import geometry for any fixturing devices that could conceivably interfere with the cutting tool.

After the geometry has been imported, the workpiece is oriented and positioned such that it is aligned with the coordinate system of the machine tool on which it will be machined. At this point, the machining operations can be specified. Some of the more common machining operations and their definitions include

Pocketing. This refers to the act of removing *all* material inside a closed boundary to a uniform depth.

Contouring. This refers to removing material exactly along a contour. The stock inside and outside the contour is not machined.

Face milling. This refers to flattening the face of a workpiece. This is frequently the first operation performed when working with a plate because it establishes a reference height for subsequent features.

Drilling. One or more holes are drilled according to the parameter specified.

For each type of machining operation specified, the user must define an appropriate set of parameters. Default values based on the workpiece material and specified cutting tool streamline the process. However, the user still must specify certain pieces of information, such as how much stock to leave in a roughing operation, the type of cutting tool to use (flat end mill, ball end mill, twist drill, etc.), the type of lead-in and lead-out to use, the depth per pass, etc.

When all of the machining operations and their parameters have been specified, it is customary to conduct a graphic toolpath verification for each separate machining operation to ensure that the cutting tools cut geometry as intended and that they don't collide with anything. However, almost all CNC machine operators can say from painful experience that graphic toolpath verification is not foolproof. Most CNC machines have a wide variety of tool offsets, fixture offsets, machine offsets, etc. For example, a toolpath is generated assuming that the (0, 0, 0) reference point is the top, left, rear corner of a block that is clamped in a vise. When the part is clamped in the vise on the actual machine, the operator must remember to measure the height of the top surface of the block relative to the machine's coordinate system. Note that the top of the part is almost always

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higher than the machine's $z = 0$ position. This z-offset value must be entered. If the operator forgets to do this, the machine will run the program at a lower z-height than was intended. In the simplest case, this leads to a broken tool. In the extreme, it can lead to a collision that damages the spindle of the machine.

Figure 6.6 shows a Solidworks CAD model of a connecting rod that has been mounted on a modular fixturing plate. The fixturing plate, locating pins, and toggle clamps all can be downloaded from online databases. For this particular machining setup, the top face of the boss on either end of the connecting rod is to be faced, and the holes are to be reamed. This CAD assembly was imported into the SurfCAM software package, where the CNC toolpath was generated. For illustrative purposes, the clearance plane for the cutting tool was intentionally set too low so that the cutting tool would collide with the vertical toggle clamp that holds the part down. Figure 6.7 shows a snapshot from the graphic toolpath verification with the cutting tool above the left boss. Note the unintended slot through the vertical toggle clamp that resulted from the improper z-clearance plane. Although this example was contrived, it shows the value of including both the part to be machined and any workholding devices in the toolpath simulation procedure.

6.3 Computer-Aided Engineering

Computer-aided engineering (CAE) refers to a host of different software packages that help engineers and machinists to design

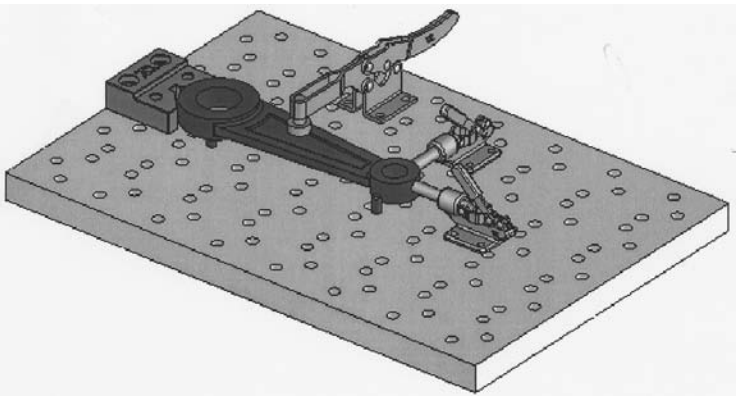

Figure 6.6 Connecting rod and machining fixture.

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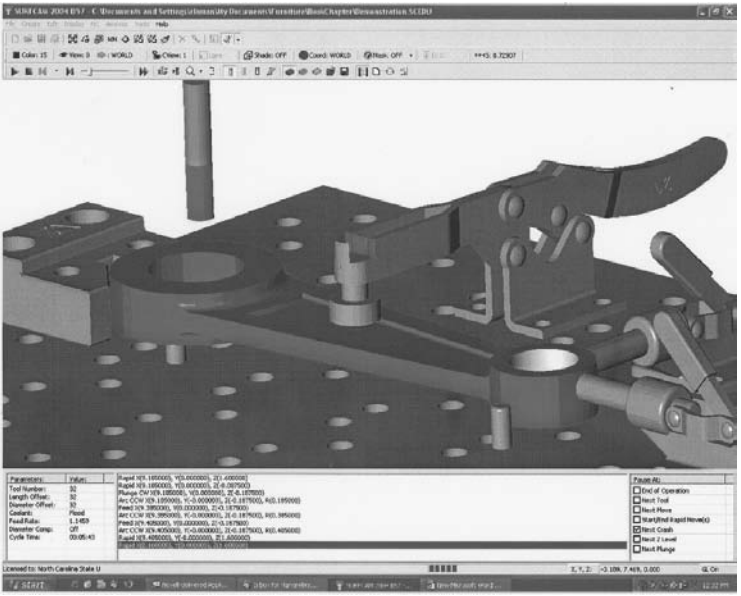

Figure 6.7 Graphic toolpath verification.

TABLE 6.8 CAE Design Automation Software

Company	URL	Related product(s)
CAPVIDIA	*www.capvidia.com*	FaceWorks
EasyMold	*www.easymold.de*	EasyMold
Manusoft Technologies Pte, Ltd.	*www.imold.com*	IMOLD
Moldex3D	*www.moldex3d.com*	Moldex3DWorks
Moldflow Corp.	*www.moldflow.com*	Moldflow Plastics Advisors
R&B, Ltd., MoldWorks	*www.RnBUSA.com*	MoldWorks and SplitWorks

and analyze systems. Of particular interest to machinists and metalworkers are software packages that help to automate the tool and die design process. Table 6.8 provides a listing of several companies that provide CAE software for a variety of tasks of interest to machinists and metalworkers.

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Computer-Aided Design, Manufacturing, and Engineering Systems

Even without using a third-party CAE package, most CAD solid modelers provide the tool and die maker with numerous useful CAE tools. One such tool is motion analysis. With motion analysis, the tool designer has the ability to model the movement of all components in a tool as it will go in its normal range of motion on the shop floor. For instance, the designer might simulate a complex mold with slides, lifters, etc. opening and closing. Progressive dies for sheet metal are also complex tools whose motion can be simulated. Throughout the motion simulation, the CAD system can check for interferences between components and can warn the designer of possible collisions. This sort of virtual testing can be done before a single metal chip has been cut. More advanced finite-element simulation models can even simulate expansion of components as they heat up in operation.

Many third-party software packages are aimed at streamlining the tool design process. Figure 6.8 shows the CAD model for a small plastic reflector dome used in a handheld flashlight. Programs such as Moldworks and Splitworks are designed to automate portions of the mold design process in the CAD system. Moldflow Mold Advisor is an example of a program that will analyze plastic parts and their molds to predict problems such as trapped air, short shots, etc. For a given part, the software will recommend the best gate location(s). When the user has specified one or more gate locations, the software then simulates the cavity filling with plastic, as shown in Fig. 6.9. Based on the simulation of how the mold fills, the software then will warn the designer of potential problems with warping, sink marks, or trapped air. If a potential problem exists, the designer can use the analysis to redesign the

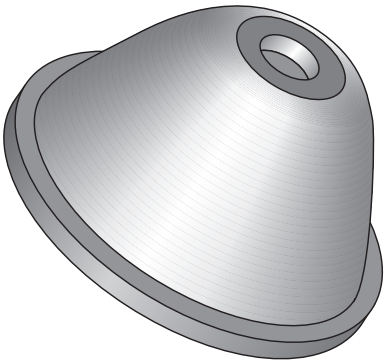

Figure 6.8 CAD model of plastic reflector dome.

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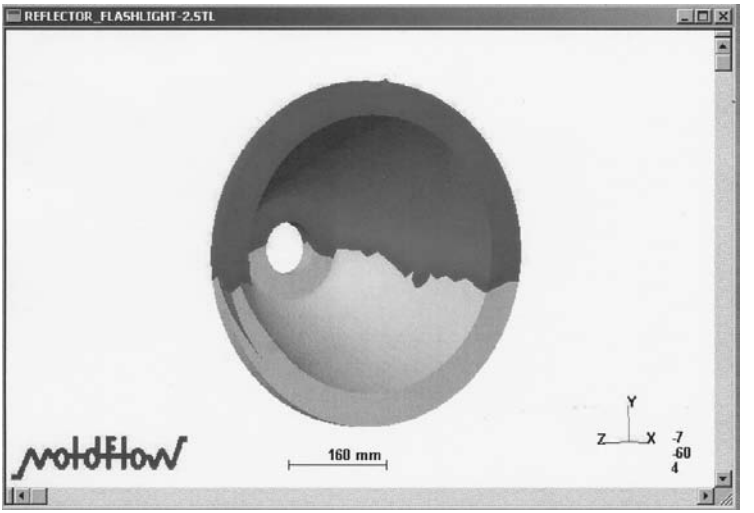

Figure 6.9 Moldflow filling simulation analysis.

mold. For instance, he or she may choose to relocate a gate, add vents, etc.

6.4 Product Data Management

Product data management (PDM) means different things to different people. A great deal of information is generated in any product-development effort. The CAD model represents just a small fraction of the information associated with a new product. Each major department within a company uses information in a different way, yet the departments often share the same information. As a simple example, the mechanical designer may generate a CAD model. He or she is concerned primarily with the mechanical function of the product. The manufacturing department will use those CAD models to design tooling. The purchasing department will use the CAD models to determine which components must be purchased and what the specifications are for those "buy" items. Sales and marketing might derive costing data from CAD models generated by both the design and manufacturing departments.

What is clear from this discussion is that the same information is used by a wide variety of departments within a company. Whether

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it is a small firm with fewer than 20 employees or a large multinational firm with tens of thousands of employees, changes made to a single piece of information can have far-reaching effects. This is where PDM software comes into play. PDM software packages typically provide some or all of the following functions:

- They manage consistency of the data so that the same piece of information is not stored in multiple locations and so that a change in a piece of information immediately propagates to all applications that use that information.
- They prevent unauthorized changes to data.
- They manage revision histories.
- They control the "check-in" and "check-out" of data so that multiple users are not simultaneously attempting to modify the same document.

Some PDM packages are designed for workgroup-level implementations that are appropriate for use in small companies that are confined to a single building. These packages can cost as little as a few thousand dollars. Other PDM packages provide enterprise-wide solutions for global companies. These systems can cost hundreds of thousands to even millions of dollars for turnkey installations. A listing of selected PDM vendors is provided in Table 6.9.

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TABLE 6.9 Selected PDM Vendors

Company	URL	Related product(s)
Agile Software Corp.	*www.agile.com*	Agile PLM, Agile Configurator
ARC Solutions, Ltd.	*www.arcsolutions.de*	REMARC
Arena Solutions	*www.arenasolutions.com*	Arena SolidWorks Integration Adapter
Assetium	*www.assetium.com*	@UDROS
Auto-Trol	*www.auto-trol.com*	Centra 2000
Baan PLM	*www.baan.com*	iBaan PLM Integration for SolidWorks, Baan PDM
CAD-Partner	*www.cadpartner.de*	SMAP 3D PartFinder and Organizer
CadWorks Software Oy, Ltd.	*www.cadworkssoftware.com*	CustomWorks
Cegid	*www.cegid.fr*	ISOFLEX
Centare Group, Ltd.	*www.centare.com*	SimplePDM
CONTACT Software GmbH	*www.contact.de*	CIM DATABASE
CYCO Software BV	*www.cyco.com*	AutoManager Meridian
Delta Group, Ltd.	*www.deltagl.com*	TreeWorks
EIGNER PARTNER AG	*www.ep-ag.com*	Axalant, CADIM/EDB
Elton Solutions, Ltd.	*www.eltonsolutions.com*	RevZone
EMCAD	*www.emcad.nu*	EasyWorks
Engineering PLM Solutions srl	*www.engineeringplmsolutions.com*	EDM 2004
Engineering S.P.A.	*www.engineering.it*	Engineering DataCenter Manager
ERP Competec Oy	*www.competec.com*	PD Spiner for SolidWorks
GCS Scandinavia AB	*www.conisio.com*	Conisio
Gedas Deutschland GmbH	*www.gedas.com*	SAP R/3 Integration for SolidWorks, SAP R/3 Integration for Solid Edge
ICON Informationssyteme GmbH	*www.swgain.de*	SwGain
ICoolSoft	*www.cool-soft.com*	CoolWorks
Integrated Dynamic Solutions	*www.integrateddynamicsolutions.com*	DataValve
Itworks, Inc.	*www.itworksaok.com*	DataBridge

TABLE 6.9 Selected PDM Vendors (*Continued*)

Company	URL	Related product(s)
Keytech software GmbH	*www.keytech.de*	ProfiDB
Lascom	*www.lascom*	Advitium
Logic Design Corp.	*www.ldcglobal.com*	Global Edge
Logotec Engineering S.A.	*www.logotec.com.pl*	PDM9000
MatrixOne, Inc.	*www.matrixone.com*	eMatrix SolidWorks, Matrix One
Maxxsoft GmbH	*www.maxxsoft.com*	MaxxDatabase
MechWorks	*www.mechworks.com*	DBWorks
Modultek, Inc.	*www.solidpdm.com*	SolidPDM
OLE Technology Co., Ltd.	*www.ole-tech.com*	SmarGroup
PROCAD GmbH & Co. KG	*www.procad.de*	PRO.FILE
Product Sight Corporation	*www.productsight.com*	Find View
Protetus Systems, Inc.	*www.proteus-global.com*	CDD Systems
Questica	*www.questica.com*	Questica 2000
ReadySolutions	*readysolutions.it*	Ready2Works
SDH Development	*www.tooworks.info*	ToolWorks ERP Link
SIGHT Informationssysteme GmbH	*www.sight.de*	Sight/EDM
SMARTEAM/Dassault Systemes	*www.smarteam.com*	SMARTEAM
SofTech, Inc.	*www.softech.com*	ProductCenter
SOLID Applications, Ltd.	*www.solidapps.co.uk*	Drawing ManEdger
SolidWorks	*www.solidworks.com*	PDMWorks

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Chapter

7

Machining, Machine Tools, and Practices

Machine tools and cutting tools have advanced in great strides in the past 50 years. What at one time was a difficult operation on a machine tool such as a lathe or milling machine has become commonplace and greatly simplified with the advent of microprocessor controls, advanced positioning and control techniques, and modern cutting tool materials. Chapter 1 described some of the modern equipment that is standard in many companies throughout the nation and the world. This chapter discusses other types of equipment, controls, and cutting tools, together with their applications to machining and metalworking practices.

Over the past 50 years, cutting tools have progressed from high-carbon steel, high-speed steel, cobalt matrix, and solid carbides to cemented or sintered carbides, ceramics, silicon nitride, cubic boron nitride, and special cutting tool coatings such as titanium nitride, titanium carbide, aluminum oxide, and others. The advantages of these new technologies in cutting tools have been increased production rates coupled with cost savings. Cutting tool technology is changing constantly, with new types of cutters, mills, drills, reamers, etc. being introduced to the market at a steady pace.

This chapter will show the latest types of cutting tools, together with the important speeds and feeds recommended for them. Also

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shown are the typical speeds and feeds for the popular and widely used high-speed-steel (HSS) and cobalt-matrix tools. The speeds and feeds tables for the various materials and machining methods are provided by the manufacturers who produce the cutting tools. Their research and development efforts, coupled with their experience and expertise, will be appreciated by those who use these tables.

7.1 Turning and Boring

Turning is the machining process used to generate external cylindrical forms by removing material, usually with a single-point cutting tool. *Boring* is essentially internal turning to generate internal shapes. The common turning machines include engine lathes, single-spindle automatic lathes, horizontal-turret lathes, automatic screw machines, Swiss-type automatic screw machines, multiple-spindle automatic bar and chucking machines, and computer-controlled automatic turning centers. The single-point tool is moved parallel to the machine spindle for straight or contour turning of the outside diameter and turning or boring of an internal surface. Form tools, both flat and circular, were at one time fed into the workpiece to produce the desired contour on the part. Knurling produces a controlled rough surface pattern on the periphery of the part, either diamond-shaped or straight, in coarse, medium, or fine texture.

7.1.1 Turning and boring tool materials

High-speed steel (HSS), cast nonferrous alloys (Stellite and Tantung), and cemented carbides (sintered carbides) are among the most widely used turning, milling, and boring tool bit materials. The more advanced materials used for turning, boring, and milling operations include the following families:

- Tungsten carbides, coated (aluminum oxide and titanium nitride) and uncoated
- Cermets (ceramics with metallic binders)—titanium carbide and titanium nitride with a metallic binder
- Ceramics—alumina-base (aluminum oxide) and silicon nitride–base ceramics
- Polycrystallines—polycrystalline diamond and cubic boron nitride

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Machining, Machine Tools, and Practices

Popular grades of HSS and Tantung (cast-alloy) tool bits

HSS and cobalt ground tool bits

M-2 HSS. General-purpose tool bit material. Works extremely well on mild steel, alloys, and tool steels and is an excellent finishing tool. Hardness: Rockwell C 63 to C 65.

5% cobalt. For heavy cuts on castings and forgings. A T-4 type of tungsten HHS that withstands higher heat than M-2 types. Hardness: Rockwell C 64 to C 66.

10% cobalt. A superior type of HHS used for heavy cuts in hard materials. Hardness: Rockwell C 64.5 to C 67.5.

Cobalt M-34. For heavy cuts on castings and forgings. A T-4 type of tungsten HSS that withstands higher heat than M-2 types.

Cobalt M-43. A superior type of HSS that is excellent for high-heat applications and for heavy cuts in hard materials.

Tantung tool bits

Tantung G. A cast-alloy cutting tool material composed of chromium, tungsten, columbium, and carbon in a cobalt matrix. These materials have the ability to retain cutting hardness at temperatures up to 1500°F. As a cutting tool, Tantung G is excellent for all turning, boring, facing, milling, and cutoff applications on most metal and nonmetallic materials. Performs best at cutting speeds of 100 to 250 surface feet per minute (sfpm). Hardness: Rockwell C 60 to C 63 and transverse rupture strength of 300,000 psi, minimum.

Note: Typical modern high-speed turning and boring tool materials and insert forms are shown following the speeds and feeds tables in this section.

7.1.2 Turning tool types, terms and definitions, and grinding

Single-point tools. A typical set of turning tools of HSS is shown in Fig. 7.1, together with a straight-shank lathe tool holder. The unground and ground tool bits are shown under the tool holder, followed by the different configurations of basic cutting bits. The cutting bit types are as follows:

A Left-hand turning tool

B Round-nose turning tool

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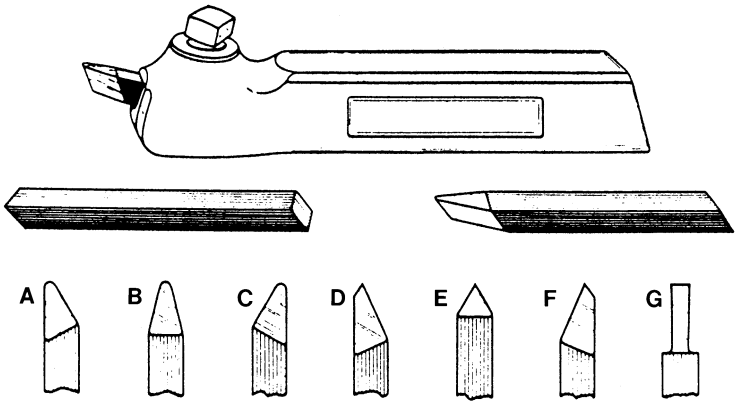

Figure 7.1 Standard lathe cutting tools.

C Right-hand turning tool
D Left-hand facing tool
E Threading tool
F Right-hand facing tool
G Cutoff tool

Applications for the cutting tools are shown in Fig. 7.2 and include turning, facing, threading, cutoff, boring, and inside threading. The important geometric form angles relating to single-point cutting tools that are ground from HSS and cast-alloy bit-stock materials (Tantung, Tantung G, Stellite, etc.) are shown in Fig. 7.3.

7.1.3 Tool nomenclature

A single-point tool contains several geometric elements that are classified and defined by the American National Standards Institute (ANSI) B94.50-1975 (R1986), *Single-Point Cutting Tools, Basic Nomenclature and Definitions for*. The basic definitions may be summarized as follows:

The *size* of a tool of square or rectangular section is expressed by giving, in the order named, the width of the shank w, the height of shank h, and the total tool length l in inches, such as $0.75 \times 1.50 \times 8$ in.

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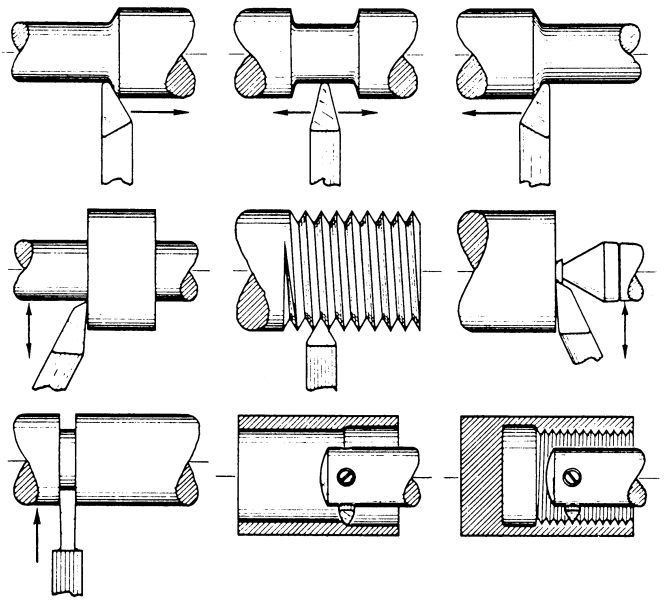

Figure 7.2 Turning operations.

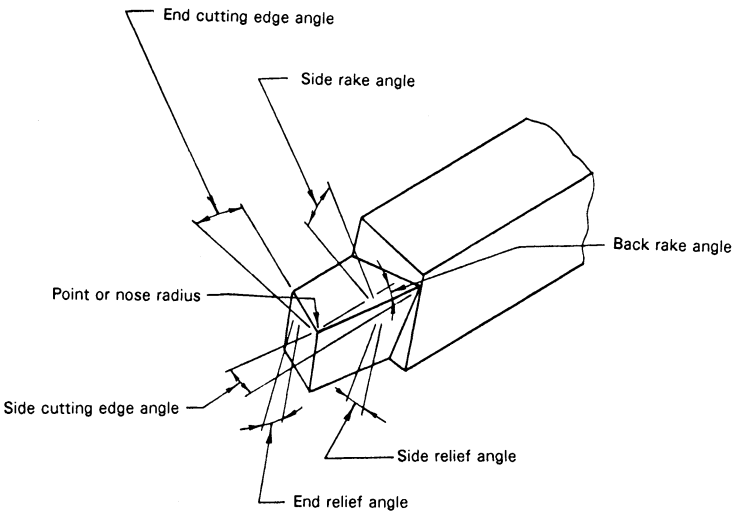

Figure 7.3 Form angles of a single-point cutting tool.

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The *shank* is that part of the tool on one end of which the point is formed or the tip or bit is supported. It is supported on the tool post of the machine.

The *base* is that surface of the shank which bears against the support and takes the tangential pressure of the cut.

The *heel* consists of the areas adjacent to the intersection of the base and flank.

The *face* is the surface on which the chip apparently impinges as it is separated from the workpiece. It may be provided with a narrow land ground along the cutting edge to support the built-up edge. This land is usually of less rake than that of the balance of the face. The face rake is then often greater than normal. For sintered-carbide tools, the land may be ground to a negative rake.

The *tool point* is all that part of the tool which is shaped to produce the cutting edges and face.

The *cutting edge* is the portion of the face edge along which the chip is separated from the workpiece. It consists usually of the side-cutting edge, the nose, and the end-cutting edge.

The *nose* is the corner, arc, or chamfer joining the side-cutting and the end-cutting edges.

The *flank* of the tool is the surface or surfaces below and adjacent to the cutting edge.

The *neck* is an extension of the shank of reduced cross-sectional area. A small point, as required in boring operations, is sometimes attached to the shank by a neck.

The *flat* or *drag* is the straight portion of the end-cutting edge at 0° intended to eliminate feed marks and produce a smooth machined surface.

A typical single-point carbide-tipped turning tool is shown in Fig. 7.3, and the angles shown are normal, that is, taken with reference to the cutting edges, since these are the ones specified in grinding a single-point tool. If a land is used, the rake of the land is given, followed by the rake of the face, such as –3 (12). This indicates a land rake of negative 3° with a positive side rake of 12°.

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7.1.4 Tool angles

The tool angles shown in Fig. 7.4 are defined as follows:

Back-rake angle. The angle between the face of the tool and the base of the shank or holder. This is usually measured in a plane through the side-cutting edge and at right angles to the base. It is positive if the face slopes downward from the point toward the shank, tending to reduce the included angle of the tool point. It is negative if the face slopes upward toward the shank.

Side-rake angle. The angle between the face of the tool and the base of the shank or holder. It is usually measured in a plane perpendicular to the base and to the side-cutting edge and hence is normal side rake.

Side-relief angle. The angle between the portion of the side flank immediately below the side-cutting edge and a line drawn through this cutting edge perpendicular to the base. It is usually measured in a plane at right angles to the side flank and hence is normal side relief.

End-relief angle. The angle between the portion of the end flank immediately below the end-cutting edge and a line drawn

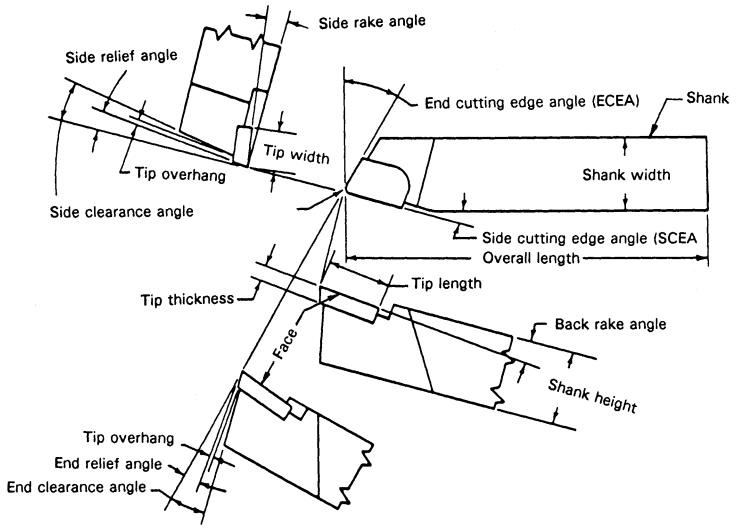

Figure 7.4 Tool angles and definitions.

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through that cutting edge perpendicular to the base. It is usually measured in a plane at right angles to the end flank and hence is normal end relief.

Clearance angle. The angle between a plane perpendicular to the base of the tool or holder and that portion of the flank immediately below the relieved flank. Side-clearance angle is measured in the plane of the back-rake angle. The clearance angle is greater than its corresponding relief angle, except when only one plane exists on the flank, in which case the clearance and relief angles coincide.

Side-cutting-edge angle. The angle between the straight side-cutting edge and the side of the tool shank or holder.

End-cutting-edge angle. The angle between the cutting edge on the end of the tool and a line at right angles to the side of the tool shank.

Note: As the setting of the tool or holder is changed in relation to the workpiece, the *effective working angles* will no longer agree with the tool angles.

Tool character. An abbreviated, convenient designation system for specifying the angles of single-point cutting tools is shown in Fig. 7.5. These angles are considered normal as used in most tool specifications and in grinding operations.

Working angles. Working angles are the angles between the tool and the workpiece. These angles depend on the shape of the tool, as well as on its position relative to the workpiece. These angles are defined as follows:

Setting angle. The angle made by the straight portion of the shank of a tool or holder with the machined portion of the workpiece, commonly 90°.

Entering angle. The angle that the side-cutting edge of a tool makes with the machined surface of the workpiece, which is 90° in the case of a tool with 0° side-cutting-edge angle effective.

True rake angle. The slope of the tool face toward the tool base, from the active cutting edge in the direction of chip flow.

Cutting angle. The angle between the face of the tool and a tangent to the machined surface at the point of action. This angle is equal to 90° minus the true rake angle.

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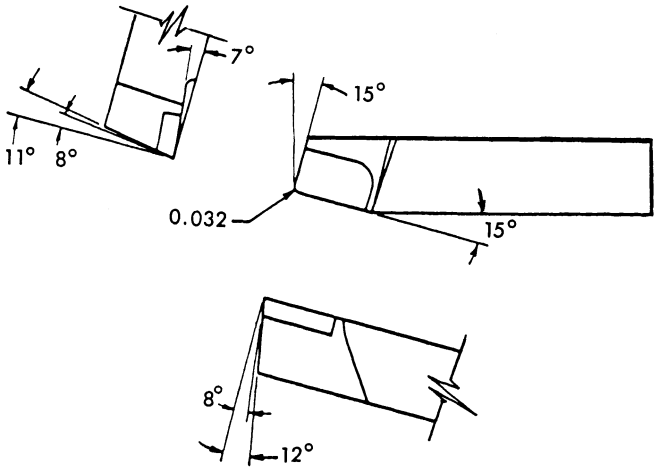

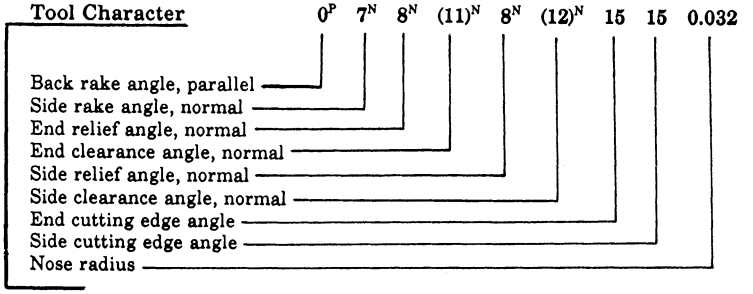
Tool Character
0^P 7^N 8^N (11)^N 8^N (12)^N 15 15 0.032
Back rake angle, parallel
Side rake angle, normal
End relief angle, normal
End clearance angle, normal
Side relief angle, normal
Side clearance angle, normal
End cutting edge angle
Side cutting edge angle
Nose radius

Figure 7.5 Tool character system.

Lip angle. The included angle of the tool material between the face and the relieved flank. According to the direction of measurement, it may represent the end lip angle, side lip angle, or true lip angle.

Working-relief angle. The angle between the relieved ground flank of the tool and a line tangent to the machined surface passing through the active cutting edge.

Working end-cutting-edge angle. The angle between the end-cutting edge and a plane tangent to the machined surface at the point of cutting.

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7.1.5 Selection of tool geometry

Rake angles. The rake-angle combination varies greatly according to tool material, workpiece material, and cost. Thermally efficient cutting is improved with positive rake angles or at least positive rake angles with respect to chip flow or true rake. It should be understood that a high positive rake results in a more fragile cutting edge and often must be compromised for tool durability. As cutting speeds increase, the rake angle has less effect on tool pressures. Therefore, in using tool materials that can be operated at higher cutting speeds, it becomes possible to use less positive rake angles or even negative rakes to increase tool strength and economize on tool maintenance. Prismatic-insert and throwaway-insert tools are greatly simplified in use and maintenance by using negative rake angles, although more cutting power and increased cutting forces are required.

Combining negative back rake with positive side rake allows safer cutting through slots or keyways, thus placing the initial impact loads on a portion of the cutting edge removed from the nose of the tool bit.

Relief angles. Side and end relief angles vary between 5° and 15° for cutting metals and may run higher for some of the nonmetallic materials. Increased relief angles reduce cutting forces and result in a cleaner cut on low-tensile-strength materials. Reduced relief angles give more support to the cutting edge of the tool and are indicated for cutting high-strength metals. A wear land of excessive width may be the result of too small a relief angle, and tool breakage downward from the cutting edge may result from too large a relief angle.

Cutting-edge angles. The shape of the workpiece often determines the side-cutting-edge angle. Side-cutting-edge angles of approximately 15° will reduce the cutting power requirement, increase tool life, and aid in controlling the chip. A greater angle increases the chip thickness or makes an increase in feed possible. A decreased side-cutting-edge angle reduces the force at right angles to the workpiece and is required on thin-walled or long, slender workpieces.

End-cutting-edge angles of 6° to 15° are common. An angle of less than 6° may cause excessive forces normal to the work surface and lead to rapid dulling of the cutting tool. Angles greater than 15° may weaken the tool point but are used for tracing tools that must "in-feed" while operating. In all cases, the end-cutting-edge angle should be a minimum of 4° in relation to the surface of the workpiece.

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A modification of the end-cutting-edge angle to 0° for a distance a little greater than the feed will produce a drag, or flattening, effect on the tool feed mark. If this modification is used, it must have a relief angle under it.

Nose radius. A small nose radius reduces cutting forces and is indicated on long, slender parts or thin-walled sections. Large nose radii make the tool stronger and are indicated for roughing operations. Large radii also generally are used for machining cast iron and similar materials that produce a crumbling chip.

Chipbreaker. A chipbreaker is a small step or groove in the face of a tool or a separate piece attached to the tool or toolholder that causes the chip to break into small sections or curl. The three common types of chipbreakers are those which are ground into the tool point, those which are attached to the tool point, and those which are preformed into an insert. Figure 7.6 shows a typical removable insert toolholder and support for an engine lathe. The removable cutting insert shown mounted on the end of the toolholder has a chipbreaker groove formed into its perimeter.

Figure 7.7 shows a typical modern engine lathe with its ACU-RITE III digital readout panel at the upper left. Sensors on the lathe send digital electronic signals to the readout panel so that the

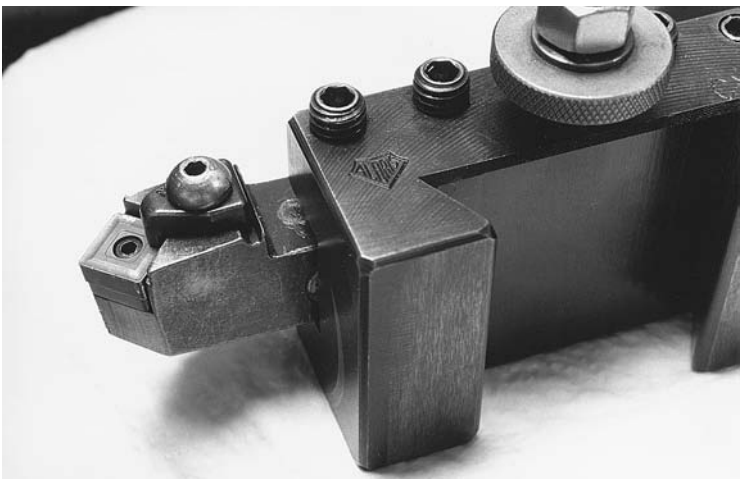

Figure 7.6 Close-up view of a turning insert and toolholder.

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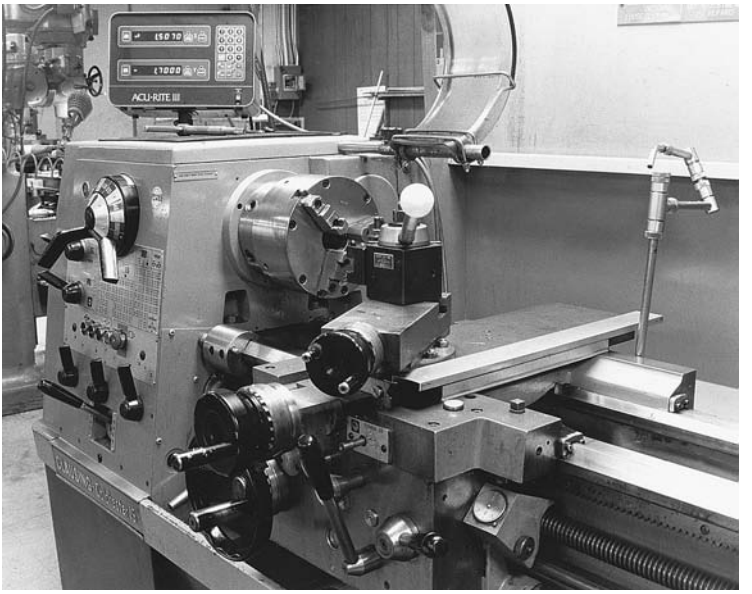

Figure 7.7 Typical engine lathe with digital control panel.

operator can set all the controls and movements to a precision of ±0.0005 in without reading the vernier dials on the machine. This allows higher productivity, with less chance of machine operator errors owing to incorrect reading of the mechanical verniers on the machine's controls. The toolholder clamp knob for clamping the toolholder shown in Fig. 7.7 can be seen directly to the right of the three-jaw chuck.

Cutting angles for single-point cutting tools (HSS, cast-alloy, and carbide)

Cutting angles for HHS cutting tools. Figure 7.8 shows the recommended cutting angles for HSS lathe tool bits. Figure 7.9 shows the recommended cutting angles for cast-alloy (Stellite, Tantung/Tantung G, etc.) lathe tool bits. Figure 7.10 shows the recommended cutting angles for carbide lathe bit tools.

7.1.6 Grinding/sharpening of HSS, cast-alloy, and carbide tool bits

Proper grinding and sharpening of standard tool-bit materials should produce a surface condition that promotes a substantial

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Recommended Angles for HSS (High-speed-steel) Single-point Tools - (Tabular data in degrees)

Material	Side-relief angle	Front-relief angle	Back-rake angle	Side-rake angle
High-speed, alloy and high-carbon tool steels and stainless steels	7 - 9 (8)	6 - 8 (8)	0 - 7 (0)	8 - 10 (8)
SAE steels:				
1020, 1035, 1040	8 - 10 (8)	8 - 10 (8)	0 - 12 (0)	8 - 12 (8)
1045, 1095	7 - 9 (8)	8 - 10 (8)	0 - 12 (0)	8 - 12 (8)
1112, 1120	7 - 9 (8)	7 - 9 (8)	0 - 14 (0)	10 - 14 (10)
1314, 1315	7 - 9 (8)	7 - 9 (8)	0 - 14 (0)	10 - 16 (10)
1335	7 - 9 (8)	7 - 9 (8)	0 - 14 (0)	10 - 16 (10)
3115, 3120, 3130	7 - 9 (8)	7 - 9 (8)	0 - 10 (0)	8 - 12 (8)
3135, 3140	7 - 9 (8)	7 - 9 (8)	0 - 10 (0)	8 - 10 (8)
3250, 4140, 4340	7 - 9 (8)	7 - 9 (8)	0 - 8 (0)	8 - 10 (8)
6140, 6145	7 - 9 (8)	7 - 9 (8)	0 - 8 (0)	8 - 10 (8)
Aluminum & alloys	12 - 14 (14)	(14)	(0)	(15)
Phenol formaldahyde (Bakelite)	(14)	(14)	(0)	(10)
Brass, free-cutting	10 - 12 (10)	8 - 10 (10)	(0)	1 - 8 (8)
Bronzes-cast, red, yellow	8 - 10 (10)	8 - 10 (10)	(0)	-4 to +6 (+6)
Bronze, free-cutting	8 - 10 (10)	8 - 10 (10)	(0)	2 - 6 (6)
Phosphor-bronze, hard	8 - 10 (10)	6 - 10 (10)	(0)	0 - 6 (6)
Cast iron, gray	8 - 10 (8)	6 - 8 (8)	0 - 5 (0)	8 - 12 (8)
Copper	12 - 14 (12)	12 - 14 (12)	0 - 16 (0)	12 - 20 (12)
Copper alloys:				
Hard	8 - 10 (10)	6 - 10 (10)	(0)	0 - 8 (8)
Soft	10 - 12 (12)	8 - 12 (12)	0 - 2 (0)	0 - 10 (10)
Fiber	14 - 16 (14)	12 - 14 (14)	0 - 2 (0)	0 - 10 (10)
Formica	14 - 16 (14)	10 - 14 (14)	0 - 16 (0)	10 - 12 (12)
Nickel iron	14 - 16 (14)	10 - 14 (14)	0 - 8 (0)	12 - 15 (15)
Micarta	14 - 16 (14)	10 - 14 (14)	0 - 16 (0)	10 - 15 (15)
Monel and nickel	14 - 16 (14)	12 - 14 (14)	0 - 10 (0)	12 - 15 (15)
Nickel silvers	10 - 14 (14)	10 - 14 (14)	0 - 10 (0)	0 - 10 (10)
Rubber, hard and plastics	18 - 20 (20)	14 - 20 (20)	(0)	0 - 20 (20)

NOTE: Angles in parentheses are recommended as a starting point.

Figure 7.8 Angles for HSS single-point tools.

Recommended Cutting Angles for Cast-Alloy Tools * - (Tabular data in degrees)

Material	Back-rake angle	Side-rake angle	Side-relief angle	Front-relief angle	Side-cutting-edge angle	End-cutting-edge angle
Steel	8 - 20 **	8 - 20 **	6	6	10	15
Cast steel	8	8	6	6	10	15
Cast iron	0	4	6	6	10	15
Bronze	4	4	6	6	10	10
Stainless steel	8 - 20 **	8 - 20 **	6	6	10	15

* Stellite 98M-2 turning tools & Tantung/Tantung "G"
** Angles depend on grade and type of steel. Soft materials require more positive rake than hard materials.
Boring tools use the same rake but greater relief to clear the workpiece.

Figure 7.9 Angles for cast-alloy tools.

Recommended Angles for Carbide Single-point Tools - (Tabular data in degrees)

Material	Normal end relief	Normal side relief	Normal back rake	Normal side rake
Aluminum & magnesium alloys	6 - 10 (10)	6 - 10 (10)	0 to 10 (10)	10 to 20 (15)
Copper	6 - 8 (8)	6 - 8 (8)	0 to 4 (0)	15 to 20 (15)
Brass and bronze	6 - 8 (8)	6 - 8 (8)	0 to -5 (0)	+8 to -5 (+8)
Cast iron	5 - 8 (6)	5 - 8 (6)	0 to -7 (0)	+6 to -7 (-6)
Low carbon steels to SAE 1020	5 - 10 (6)	5 - 10 (6)	0 to -7 (0)	+6 to -7 (+6)
Carbon steels, SAE 1025 and above	5 - 8 (6)	5 - 8 (6)	0 to -7 (0)	+6 to -7 (+6)
Alloy steels	5 - 8 (6)	5 - 8 (6)	0 to -7 (0)	+6 to -7 (+6)
Free machining steels SAE 1100 and 1300	5 - 10 (6)	5 - 10 (6)	0 to -7 (0)	+6 to -7 (+6)
Stainless steels, austenitic	5 - 10 (6)	5 - 10 (6)	0 to -7 (0)	+6 to -7 (+6)
Stainless steels, hardenable grades	5 - 8 (6)	5 - 8 (6)	0 to -7 (0)	+6 to -7 (+6)
High nickel alloys (Monel, Inconel, etc.)	5 - 10 (8)	5 - 10 (8)	0 to -3 (0)	+6 to +10 (+10)
Titanium alloys	5 - 8 (6)	5 - 8 (6)	0 to -5 (0)	+6 to -5 (+6)

NOTE: Angles in parantheses are recommended as a starting point.

Figure 7.10 Angles for carbide tools.

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increase in the number of workpieces produced per grind. First, grind the tool bit to the proper angles using an aluminum oxide wheel of 40 to 60 grit, followed by a 320-grit aluminum oxide wheel. The second step should remove only a minimal amount of material, on the order of 0.0005 to 0.001 in. If hand honing of the tool is attempted, a hard Arkansas or medium India stone should be used. An experienced operator is required for hand honing tool bits.

7.1.7 Turning operation calculations

Cutting speed. Cutting speed is given in surface feet per minute (sfpm) and is the speed of the workpiece in relation to the stationary tool bit at the cutting point surface. The cutting speed is given by the simple relation

$$S = \frac{\pi d_f (\text{rpm})}{12} \qquad \text{for inch units}$$

and

$$S = \frac{\pi d_f (\text{rpm})}{1000} \qquad \text{for metric units}$$

where S = cutting speed, sfpm or m/min
d_f = diameter of work, in or mm
rpm = revolutions per minute of the workpiece

When the cutting speed (sfpm) is given for the material, the revolutions per minute (rpm) of the workpiece or lathe spindle can be found from

$$\text{rpm} = \frac{12S}{\pi d_f} \qquad \text{for inch units}$$

and

$$\text{rpm} = \frac{1000S}{\pi d_f} \qquad \text{for metric units}$$

Example: A 2-in-diameter metal rod has an allowable cutting speed of 300 sfpm for a given depth of cut and feed. At what revolutions per minute (rpm) should the machine be set to rotate the work?

$$\text{rpm} = \frac{12S}{\pi d_f} = \frac{12(300)}{3.14 \times 2} = 573 \text{ rpm}$$

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Set the machine speed to the next lowest even speed that the machine is capable of attaining.

Lathe cutting time. The time required to make any particular cut on a lathe may be found using two methods. When the cutting speed is given, the following simple relation may be used:

$$T = \frac{\pi d_f L}{12FS} \qquad \text{for inch units}$$

and

$$T = \frac{\pi d_f L}{1000FS} \qquad \text{for metric units}$$

where T = time for the cut, min
d_f = diameter of work, in or mm
L = length of cut, in or mm
F = feed, ipr (inches per revolution) or mmpr (millimeters per revolution)
S = cutting speed, sfpm (surface feet per minute) or m/min

Example: What is the cutting time in minutes for one pass over a 10-in length of 2.25-in-diameter rod when the cutting speed allowable is 250 sfpm with a feed of 0.03 ipr?

$$T = \frac{\pi d_f L}{12FS} = \frac{3.14(2.25)(10)}{12(0.03)(250)} = 0.785 \text{ min or } 47 \text{ s}$$

When the revolutions per minute of the machine are known, the cutting time may be found from

$$T = \frac{L}{F(\text{rpm})}$$

where L = length of work, in
T = cutting time, min
F = feed, ipr
rpm = spindle speed or workpiece speed, rpm

Volume of metal removed. The volume of metal removed during a lathe cutting operation can be calculated as follows:

$$V_r = 12C_dFS \qquad \text{for inch units}$$

and

$$V_r = C_dFS \qquad \text{for metric units}$$

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where V_r = volume of metal removed, in^3 or cm^3
C_d = depth of cut, in or mm
F = feed, ipr or mmpr
S = cutting speed, sfpm or m/min

Note: 1 in^3 = 16.387 cm^3.

Example: With a depth of cut of 0.25 in and a feed of 0.125 in, what volume of material is removed in 1 min when the cutting speed is 120 sfpm?

$$V_r = 12C_dFS = 12 \times 0.25 \times 0.125 \times 120 = 45 \text{ in}^3$$

For convenience, the chart in Fig. 7.11 may be used for quick calculations of volume of material removed for various depths of cut, feeds, and speeds.

Machine power requirements (horsepower or kilowatts). It is often necessary to know the machine power requirements for an anticipated feed, speed, and depth of cut for a particular material or class of materials to see if the machine is capable of sustaining the desired production rate. The following simple formulas for calculating required horsepower are approximate only because of the complex nature and many variables involved in cutting any material.

The following formula is for approximating machine power requirements for making a particular cut:

$$\text{hp} = dfSC$$

where hp = required machine horsepower
d = depth of cut, in
f = feed, ipr
S = cutting speed, sfpm
C = power constant for the particular material (see Fig. 7.12)

Example: With a depth of cut of 0.06 in and a feed of 0.025 in, what is the power requirement for turning aluminum alloy bar stock at a speed of 350 sfpm?

$$\text{hp} = dfSC = 0.06 \times 0.025 \times 350 \times 4 \qquad \text{(see Fig. 7.12)}$$
$$= 2.1$$

For the metric system, the kilowatt requirement is $2.1 \times 0.746 = 1.76$ kW.

Note: 0.746 kW = 1 hp or 746 W = 1 hp.

The national manufacturers of cutting tools provide the users of their materials with various devices for quickly approximating the

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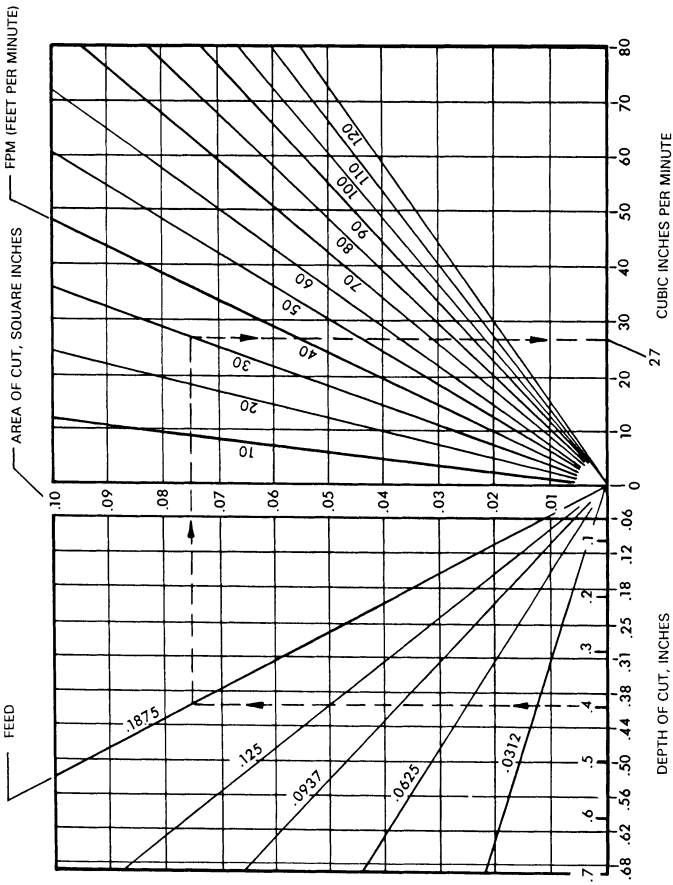

Figure 7.11 Metal-removal rate (mrr) chart.

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Power Constants for Various Metals and Alloys

Material	Constant
SAE Steels:	
1005 - 1029	6
1030 - 1050	7
1053 - 1095	8
1211 - 1215	6
1314 - 1345	6
1330 - 1350	9
1524 - 1552	9
4130 - 4820	9
5120 - 52100	10
Cast steels	9
SAE Stainless steels:	
30303, 51403, 51410, 51416	
51431, 51430F, 51440F	10
30302, 30304, 30309,30316	
30321, 51431, 51501	11
51420, 51420F, 51440A, B, C	12
Cast irons:	
Hard	4
Medium	3
Soft	3
Semi-steel	3
Malleable irons:	
Hard	5
Medium	4
Soft	3
Titanium & alloys:	
Pure	4
Alpha alloys	7
Beta alloys	8
Copper	4
Zinc alloys	3
Monel	12
Brass & bronze:	
Hard	10
Soft	4
Aluminum alloys:	
Cast	3
Bar stock	4
Magnesium alloys	3

Figure 7.12 Power constant table.

various machining calculations shown in the preceding formulas. Although formulas and calculators are available for doing the various machining calculations, it is to be cautioned that these calculations are approximations and that the following factors must be taken into consideration when metals and other materials are cut at high powers and speeds using modern cutting tools:

1. Available machine power
2. Condition of the machine
3. Size, strength, and rigidity of the workpiece
4. Size, strength, and rigidity of the cutting tool

Prior to beginning a large production run of turned parts, sample pieces are run in order to determine the exact feeds and speeds required for a particular material and cutting tool combination.

Power constants. Figure 7.12 shows a table of constants for various materials that may be used when calculating the approximate power requirements of the cutting machines.

7.1.8 Speeds, cuts, and feeds

HSS, cast-alloy, and carbide tools. The surface speed (sfpm), depth of cut (in), and feed (ipr) for various materials using HSS, cast-alloy, and carbide cutting tools are shown in Fig. 7.13. In all cases, especially where combinations of values are selected that have not been used previously on a given machine, the selected values should have their required horsepower or kilowatts calculated. Use the approximate calculations shown previously, or use one of the machining calculators available from the cutting tool manufacturers. The method indicated earlier for calculating the required horsepower gives a conservative value that is higher than the actual power required. In any event, on a manually controlled machine, the machinist or machine operator will know if the selected speed, depth of cut, and feed are more than the given machine can tolerate and can make corrections accordingly. On CNC/DNC automatic turning centers and other automatic machines, the cutting parameters must be selected carefully, with the machine operator carefully watching the first trial program run so that he or she may intervene if problems of overloading or tool damage occur.

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Recommended Cuts, Feeds and Speeds for Metals and Nonmetallic Turning - (For HSS, Cast-Alloys and Carbide Tools)

Class	Material or SAE No.	Cutting Tool Material	Depth of Cut: 0.005-0.015 Feed: 0.002-0.005	Depth of Cut: 0.015-0.094 Feed: 0.005-0.015	Depth of Cut: 0.094-0.187 Feed: 0.015-0.030	Depth of Cut: 0.187-0.375 Feed: 0.030-0.050	Depth of Cut: 0.375-0.750 Feed: 0.050-0.090
Free-cutting steels	1112, 11L17	HSS	.....	250 - 350	175 - 250	80 - 150	55 - 75
	1120	Cast-alloys	.....	425 - 550	315 - 400	215 - 300	100 -210
	1315, etc.	Sintered carbides	750 - 1,500	600 - 750	450 - 600	350 - 450	175 - 350
Carbon & low-alloy steels	1010, 1020	HSS	.....	225 - 300	150 - 200	75 - 125	45 - 65
	1025, etc.	Cast-alloys	.....	375 - 500	275 - 350	180 - 250	100 - 175
		Sintered carbides	700 - 1,200	550 - 700	400 - 550	300 - 400	150 - 300
Medium alloy steels	1030	HSS	.....	200 - 275	125 - 175	70 - 120	40 - 60
	1050	Cast-alloys	.....	325 - 400	230 - 300	160 - 225	80 - 150
		Sintered carbides	600 - 1,000	450 - 600	350 - 450	250 - 350	125 - 250
High-alloy steels	1060	HSS	.....	175 - 250	125 - 175	65 - 100	35 - 55
	1095	Cast-alloys	.....	250 - 350	200 - 250	150 - 200	65 - 150
	1350	Sintered carbides	500 - 750	400 - 500	300 - 400	200 - 300	100 -200
Chromium-nickel steels	3120, 3450	HSS	.....	150 - 200	100 - 125	50 - 75	30 - 50
	5140, 52100	Cast-alloy	.....	230 - 315	165 - 225	110 - 160	55 - 110
		Sintered carbides	425 - 550	325 - 425	250 - 325	175 - 250	75 - 175
Molybdenum steels	4130	HSS	.....	160 - 210	110 - 140	60 - 80	35 - 55
	4615	Cast-alloys	.....	250 - 325	160 - 225	120 - 150	65 - 100
		Sintered carbides	475 - 650	350 - 475	275 - 350	200 - 275	100 - 200
Chrome, vanadium and stainless steels	6120	HSS	.....	100 - 150	80 - 100	50 - 75	30 - 50
	6150, 18Cr-5Ni	Cast-alloys	.....	210 - 250	170 - 200	110 - 165	55 - 100
	6195	Sintered carbides	375 - 500	300 - 375	250 - 300	175 - 250	75 - 175
Tungsten steels	7260	HSS	.....	120 - 150	75 - 120	40 - 75	25 - 40
	18-4-1 annealed	Cast-alloys	.....	130 - 175	110 - 130	80 - 100	35 - 80
		Sintered carbides	325 - 400	250 - 325	200 - 250	150 - 200	50 - 150
Special steels	12-14% Mn.	HSS	.....	.....	.....	.....	.....
		Cast-alloys	.....	.....	.....	.....	.....
		Sintered carbides	200 - 250	125 - 200	75 - 125	50 - 75	.....

Figure 7.13 Cuts, feeds, and speeds table.

Special steels	Si. elect., sheet ingot iron, etc.	HSS	400 - 500	300 - 400	200 - 300	150 - 200	.....
		Cast-alloys	.....	500 - 600	350 - 450	250 - 300	.....
		Sintered carbide	1,000 - 1,200	800 - 1,000	600 - 800	500 - 600	.....
Cast iron	Soft gray	HSS	.....	120 - 150	90 - 120	75 - 90	35 - 75
		Cast-alloys	.....	225 - 300	160 - 220	125 - 160	70 - 125
		Sintered carbides	450 - 600	350 - 450	250 - 350	200 - 250	100 - 200
	Medium and malleable	HSS	.....	120 - 150	90 - 120	60 - 90	30 - 60
		Cast-alloys	.....	100 - 225	150 - 190	120 - 150	60 - 120
		Sintered carbides	350 - 450	250 - 350	200 - 250	150 - 200	75 - 150
	Hard alloys	HSS	.....	90 - 125	60 - 90	40 - 60	20 - 40
		Cast-alloys	.....	120 - 170	80 - 120	55 - 80	35 - 55
		Sintered carbides	250 - 300	150 - 250	100 - 150	75 - 100	50 - 75
	Chilled	HSS	10 - 15	.....	.....	.....	.....
		Cast-alloys	.....	.....	.....	.....	.....
		Sintered carbides	30 - 50	10 - 30	.....	.....	.....
Copper base alloys	Leaded, free - cutting, soft brass and bronze	HSS	.....	300 - 400	225 - 300	150 - 255	100 - 150
		Cast-alloys	.....	500 - 600	400 - 500	325 - 400	200 - 325
		Sintered carbides	1,000 - 1,250	800 - 1,000	650 - 800	500 - 650	300 - 500
	Normal brass, bronze low alloy	HSS	.....	275 - 350	225 - 275	150 - 225	100 - 150
		Cast-alloys	.....	375 - 425	325 - 375	250 - 325	175 - 250
		Sintered carbides	700 - 800	600 - 700	500 - 600	400 - 500	200 - 400
	Tough copper, high tin & alum. bronzes, gilding.	HSS	.....	100 - 150	75 - 100	50 - 75	35 - 50
		Cast-alloys	.....	225 - 300	180 - 225	125 - 180	75 - 125
		Sintered carbides	500 - 600	400 - 500	300 - 400	200 - 300	100 - 200
Light alloys	Magnesium	HSS	500 - 750	350 - 500	275 - 350	200 - 275	125 - 200
		Cast-alloys	700 - 1,000	500 - 700	400 - 500	300 - 400	200 - 300
		Sintered carbides	1,250 - 2,000	800 - 1,250	600 - 800	500 - 600	300 - 500
	Aluminum	HSS	350 - 500	225 - 350	150 - 225	100 - 150	50 - 100
		Cast-alloys	450 - 650	300 - 450	225 - 300	150 - 225	75 - 150
		Sintered carbides	700 - 1,000	450 - 700	300 - 450	200 - 300	100 - 200
Titanium	Pure & low alloys	HSS	.....	100 - 160	70 - 110	50 - 75	.....
		Cast-alloys	.....	165 - 375	110 - 250	75 - 165	.....
		Sintered carbides	550 - 900	375 - 600	250 - 400	165 - 265	.....

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	Alpha alloys	HSS	.....	30 - 75	20 - 50	.....	.....
		Cast-alloys	.....	75 - 110	50 - 75	.....	.....
		Sintered carbides	165 - 450	110 - 300	75 - 200	50 - 135	.....
	Beta alloys	HSS	.....	30 - 40	20 - 25	.....	.....
		Cast-alloys	.....	40 - 90	25 - 60	.....	.....
		Sintered carbides	125 - 225	90 - 150	60 - 100	40 - 70	.....
Plastics	Thermoplastic,	HSS	.....	.....	.....	.....	.....
	thermosetting	Cast-alloys	.....	.....	.....	.....	.....
		Sintered carbides	650 - 1,000	400 - 650	250 - 400	150 - 250	.....
Abrasives	Glass, hard	HSS	.....	.....	.....	.....	.....
	rubber, green	Cast-alloys	.....	.....	.....	.....	.....
	ceramics, marble.	Sintered carbides	150 - 250	75 - 150	.....	.....	.....

NOTE: It is possible that a combination of speeds, feeds and cuts may be so selected for a given application, that a higher horsepower may be required than is available at the lathe spindle. In all cases, especially where combinations of values are selected that have not been used previously on a given machine, the selected values should have their required horsepower calculated. See the subsection (Horsepower requirements) for calculating required horsepower when speed, feed and cut are given.
Values of depth of cut are in inches; feeds are given in ipr (inches per revolution) and speed is given in sfpm (surface feet per minute).

(Tabular values are in sfpm).

Figure 7.13 (*Continued*)

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Charts of speeds, feeds, and depths of cut for turning, boring, milling, threading, and grooving or cut off using modern machining inserts

WARNING

Cutting tools may chip or fragment in use. Always use machine guards, protective clothing, and safety glasses to prevent burns or other injury to body or eyes from flying particles or chips. Wet or dry grinding of cutting tools produces potentially hazardous dusts or mists; to avoid adverse health affects, use adequate ventilation and read material safety data sheet for applicable tool material or grade before grinding.

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Modern high-speed insert-type cutting tools. Figures 7.14 through 7.44 show the recommended ranges of starting speeds, depths of cut, and feeds for modern types of insert cutting tools. The figures shown are reprinted with permission from Valenite, Inc. Included in these figures or charts are Valenite-designated insert numbers for the various machining operations of turning, boring, milling, threading, and grooving or cut off. Figures 7.45 and 7.46 are insert cutting tool comparison charts for various manufacturers' cutting inserts, the equivalents of which are cross-referenced to the Valenite insert numbers.

(Text continued on page 383.)

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Starting Recommendations:

MACHINING OPERATIONS		- RECOMMENDATIONS - GRADE ▼	CHIPBREAKER ▼	Speed - sfm (M/min.)	Feed - ipr (mm/rev.)	Feed - ipt (mm/tooth)
TURNING & BORING	Roughing	CBN	-----	250-600 (75-180)	.003-.010 (0,07-0,25)	-----
	General Purpose	Q32	-----	300-600 (90-180)	.003-.008 (0,07-0,20)	-----
	Finishing	Q32	-----	400-700 (120-210)	.003-.006 (0,07-0,15)	-----
MILLING	Roughing	●	-----	-----	-----	-----
	General Purpose	●	-----	-----	-----	-----
	Finishing	●	-----	-----	-----	-----
Grooving & Cut Off .....➪ ALL CASES Threading .....➪		●	-----	-----	-----	-----
		●	-----	-----	-----	-----

NOTE: sfm = Surface feet/minute (Meters/Minute); ipr = Inches/revolution (mm/revolution); ipt = Inches/tooth (mm/tooth).

● Recommendations for these operations need to consider all the variables in the application (machine, tool age, coolant type, rigidity of the set up, overhangs, etc.) For product and application assistance, please contact Valenite's Technical Support Center. Phone number:(800) 488-9073.

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Figure 7.14

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Starting recommendations:

MACHINING OPERATIONS		- RECOMMENDATIONS - GRADE ▼	CHIPBREAKER ▼	Speed - sfm (M/min.)	Feed - ipr (mm/rev.)	Feed - ipt (mm/tooth)
TURNING & BORING	Roughing	SV325	GM/GR	300-500 (90-150)	.015-.030 (0,37-0,75)	-----
	General Purpose	SV315	LM/GM	400-700 (120-210)	.012-.025 (0,30-0,62)	-----
	Finishing	SV310	LF/GF	500-800 (150-240)	.004-.010 (0,10-0,25)	-----
MILLING	Roughing	V1N	-----	<400 (<120)	-----	.008-.016 (0,20-0,40)
	General Purpose	VC935M	-----	300-600 (90-180)	-----	.006-.012 (0,15-0,30)
	Finishing	VC630	-----	400-700 (120-210)	-----	.004-.007 (0,10-0,17)
Grooving & Cut Off .....➪ ALL CASES		VC121	-----	300-700 (90-210)	.004-.008 (0,10-0,20)	-----
Threading .....➪ ALL CASES		VN8	-----	300-700 (90-210)	-----	-----

Note: sfm = Surface feet/minute (Meters/Minute); ipr = Inches/revolution (mm/revolution); ipt = Inches/tooth (mm/tooth).

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CAST IRONS - ALLOYED — **CLASS 40 THROUGH CLASS 60**
SAE 60-40-10, SAE 80-60-3

Starting Recommendations:

MACHINING OPERATIONS		- RECOMMENDATIONS - GRADE ▼	CHIPBREAKER ▼	Speed - sfm (M/min.)	Feed - ipr (mm/rev.)	Feed - ipt (mm/tooth)
TURNING & BORING	Roughing	V1N	-----	250-400 (75-120)	.016-.025 (0,40-0,62)	-----
	General Purpose	SV315	GM	350-500 (105-150)	.012-.018 (0,30-0,45)	-----
	Finishing	SV310/VC929	-----	400-600 (120-180)	.004-.008 (0,10-0,20)	-----
MILLING	Roughing	V1N	-----	200-400 (60-120)	-----	.008-.016 (0,20-0,40)
	General Purpose	VC928	-----	300-600 (90-180)	-----	.006-.012 (0,15-0,30)
	Finishing	VC630/VC929	-----	400-700 (120-210)	-----	.004-.010 (0,10-0,25)
Grooving & Cut Off .....➪ ALL CASES		SV221	-----	300-600 (90-180)	.004-.010 (0,10-0,25)	-----
Threading .....➪ ALL CASES		VN8	-----	300-600 (90-180)	-----	-----

Note: sfm = Surface feet/minute (Meters/Minute); ipr = Inches/revolution (mm/revolution); ipt = Inches/tooth (mm/tooth).
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Figure 7.16

Starting Recommendations:

MACHINING OPERATIONS		- RECOMMENDATIONS - GRADE ▼	CHIPBREAKER ▼	Speed - sfm (M/min.)	Feed - ipr (mm/rev.)	Feed - ipt (mm/tooth)
TURNING & BORING	Roughing	V1N	-----	300-450 (90-135)	.016-.025 (0,40-0,62)	-----
	General Purpose	SV315	GM	400-650 (120-195)	.012-.018 (0,30-0,45)	-----
	Finishing	SV310/VC929	-----	500-700 (150-210)	.004-.008 (0,10-0,20)	-----
MILLING	Roughing	V1N	-----	300-500 (90-150)	-----	.008-.016 (0,20-0,40)
	General Purpose	VC928	-----	400-650 (120-195)	-----	.006-.012 (0,15-0,30)
	Finishing	VC929/VC630	-----	500-800 (150-240)	-----	.004-.010 (0,10-0,25)
Grooving & Cut Off .....➪ ALL CASES		SV221	-----	300-700 (90-210)	.004-.010 (0,10-0,25)	-----
Threading .....➪ ALL CASES		VN8	-----	300-700 (90-210)	-----	-----

Note: sfm = Surface feet/minute (Meters/Minute); ipr = Inches/revolution (mm/revolution); ipt = Inches/tooth (mm/tooth).

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Starting Recommendations:

MACHINING OPERATIONS		- RECOMMENDATIONS - GRADE ▼	CHIPBREAKER ▼	Speed - sfm (M/min.)	Feed - ipr (mm/rev.)	Feed - ipt (mm/tooth)
TURNING & BORING	Roughing	VC901	LM/GM	200-400 (60-120)	.016-.025 (0,40-0,62)	-----
	General Purpose	VC929	GM	300-550 (90-165)	.012-.018 (0,30-0,45)	-----
	Finishing	SV310	LF/GF	400-700 (120-210)	.004-.008 (0,10-0,20)	-----
MILLING	Roughing	V1N	-----	200-350 (60-105)	-----	.008-.016 (0,20-0,40)
	General Purpose	VC901	-----	250-500 (75-150)	-----	.006-.012 (0,15-0,30)
	Finishing	VC929	-----	400-600 (120-180)	-----	.004-.010 (0,10-0,25)
Grooving & Cut Off .....➪ ALL CASES		VC231	-----	150-300 (45-90)	.004-.010 (0,10-0,25)	-----
Threading .....➪ ALL CASES		VN8	-----	150-300 (45-90)	-----	-----

Note: sfm = Surface feet/minute (Meters/Minute); ipr = Inches/revolution (mm/revolution); ipt = Inches/tooth (mm/tooth).

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Starting Recommendations:

MACHINING OPERATIONS		- RECOMMENDATIONS - GRADE ▼	CHIPBREAKER ▼	Speed - sfm (M/min.)	Feed - ipr (mm/rev.)	Feed - ipt (mm/tooth)
TURNING & BORING	Roughing	VC901	LM/GM	250-450 (75-135)	.015-.020 (0,37-0,50)	-----
	General Purpose	VC929	GM	350-600 (105-180)	.008-.016 (0,20-0,40)	-----
	Finishing	SV310	LF/GF	400-700 (120-210)	.004-.008 (0,10-0,20)	-----
MILLING	Roughing	V1N	-----	200-350 (60-105)	-----	.008-.012 (0,20-0,30)
	General Purpose	VC901	-----	250-450 (75-135)	-----	.006-.012 (0,15-0,30)
	Finishing	VC929	-----	300-600 (90-180)	-----	.004-.008 (0,10-0,20)
Grooving & Cut Off .....➪ ALL CASES		VC231	-----	250-500 (75-150)	.004-.010 (0,10-0,25)	-----
Threading .....➪ ALL CASES		VN8	-----	250-400 (75-120)	-----	-----

Note: sfm = Surface feet/minute (Meters/Minute); ipr = Inches/revolution (mm/revolution); ipt = Inches/tooth (mm/tooth).

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Starting Recommendations:

MACHINING OPERATIONS		- RECOMMENDATIONS - GRADE ▼	CHIPBREAKER ▼	Speed - sfm (M/min.)	Feed - ipr (mm/rev.)	Feed - ipt (mm/tooth)
TURNING & BORING	Roughing	VC2	-----	200-1200 (60-360)	.008-.016 (0,20-0,40)	-----
	General Purpose	VC2	-----	400-1400 (120-420)	.008-.016 (0,20-0,40)	-----
	Finishing	VC3	-----	600 UP (180 UP)	.004-.008 (0,10-0,20)	-----
MILLING	Roughing	VC2	-----	200-1200 (60-360)	-----	.008-.012 (0,20-0,30)
	General Purpose	VC2	-----	400-1400 (120-420)	-----	.006-.012 (0,15-0,30)
	Finishing	VC29	-----	600 UP (180 UP)	-----	.004-.008 (0,10-0,20)
Grooving & Cut Off .....➪		VC121	-----	400-1200 (120-360)	.006-.014 (0,15-0,35)	-----
ALL CASES Threading .....➪		VC2	-----	400-1200 (120-360)	-----	-----

Note: sfm = Surface feet/minute (Meters/Minute); ipr = Inches/revolution (mm/revolution); ipt = Inches/tooth (mm/tooth).

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Starting Recommendations:

MACHINING OPERATIONS		- RECOMMENDATIONS - GRADE ▼	CHIPBREAKER ▼	Speed - sfm (M/min.)	Feed - ipr (mm/rev.)	Feed - ipt (mm/tooth)
TURNING & BORING	Roughing	V1N	GM/LM	75-150 (22-45)	.008-.012 (0,20-0,30)	-----
	General Purpose	VC901	LM/GF	100-200 (30-60)	.006-.010 (0,15-0,25)	-----
	Finishing	VC929	LF/GF	150-300 (45-90)	.004-.008 (0,10-0,20)	-----
MILLING	Roughing	●	-----	-----	-----	-----
	General Purpose	VC901	-----	75-150 (22-45)	-----	.006-.010 (0,15-0,25)
	Finishing	VC929	-----	100-200 (30-60)	-----	.004-.008 (0,10-0,20)
Grooving & Cut Off .....➪		●	-----	-----	-----	-----
Threading .....➪	ALL CASES	●	-----	-----	-----	-----

Note: sfm = Surface feet/minute (Meters/Minute); ipr = Inches/revolution (mm/revolution); ipt = Inches/tooth (mm/tooth).

● Recommendations for these operations need to consider all the variables in the application (machine, tool age, coolant type, rigidity of set up, overhangs, etc.). For product and application assistance, please contact Valenite's Technical Support Center. Phone number (800) 488-9073.

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Uncoated Carbide

Valenite Grade	ISO Class	Industry Class	Application	Materials	Working Methods & Conditions
VC2	M10-20 K10-20	C2	Turning, Boring & Milling	Cast-iron, copper, brass, non-ferrous Alloys, high-temp. Exotics, stone & plastics	General purpose grade of high toughness and resistance against flank wear at low to medium cutting speeds.
VC3	K10-05	C3, C4	Precision Turning, Boring, Milling	Cast-iron, aluminum, high-temperature exotics and non-ferrous materials.	Wear-resistant grade for finishing cuts, low to medium feed rates under rigid conditions.
VC5	P20-30 M20-40	C5	Turning, Boring and Milling	Steel, cast steel, malleable cast-iron, 400/500 series stainless steels.	General purpose grade with many applications, low to medium cutting speed, high feeds and depths of cut. Has good deformation resistance.
VC7	P05-15	C7	Turning, Boring, Threading and Grooving.	Steel, cast-steel, malleable cast-iron, 400/500 series stainless steels.	Light roughing to finishing at low to moderate feeds. Good crater and deformation resistance.
VC27	P15-30 M15-30 K20-30	C2	Turning and Milling	Steel, cast-steel, alloyed cast-irons, cast alloys and exotics.	General purpose fine grain grade with improved toughness and wear resistance for turning and milling.
VC28	M20-30 K15-30	C2	Milling	Cast and alloy irons.	General purpose grade for roughing to finishing in cast-irons.
VC29	M10-20 K10-20	C2, C3	Turning, Boring and Milling	Stainless steels, irons, exotics and non-ferrous materials.	Fine grain grade for finishing of exotic irons and non-ferrous metals.
VC35	P20-35	C5	Milling	Carbon, alloy steel and stainless steel.	General purpose steel milling grade for moderate roughing and finishing.
VC101	M30-40 K30-40	C1	Turning, Boring and Milling.	Iron, 200/300 stainless steel and exotics.	Fine grain heavy-duty grade for roughing at low to moderate speeds.
VC121	K05-30	C2	V-Cut plus Cut Off & Grooving	Cast Iron, aluminum, non-ferrous alloys and exotics	Medium cutting speeds and feeds.
VC135	P25-50	C5	V-Cut Plus Cut Off and Grooving.	Steel, stainless steel.	Medium speeds, heavy feeds in unfavorable conditions.

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Physical Vapor Deposition (PVD) Coated Carbides

Valenite Grade	ISO Class	Industry Class	Application	Materials	Working Methods & Conditions
VC901	M20-30 K20-30	C1	Turning, Boring, Milling, Threading, Grooving & Cut-Off	200 and 300 stainless steels, titanium alloys, nickel-based alloys, Inconel 600 and 71B, Hastelloy C, Waspalloy, cobalt-based alloys.	A micro-grained material for severe cutting conditions at low speeds. VC901 exhibits outstanding wear resistance on difficult to machine materials.
VC902	M10-20 K10-20	C2	Turning, Boring, Milling and Threading	Gray cast-iron, nickel based alloys, titanium alloys, wrought and cast aluminum.	A very tough general purpose grade with medium feed finishing cuts. Requires a very rigid set-up for optimum performance.
VC903	K01	C3, C4	Precision Turning, Boring and Milling	Gray cast-iron, nodular and malleable iron-nickel bases alloys, wrought and cast aluminum.	A highly wear resistant grade for low to medium feed finishing cuts. Requires a very rigid set-up for optimum performance.
VC905	P20-30 M20-40	C5	Turning, Boring, Threading and Grooving	Low to medium carbon steels, alloy steels, stainless steels.	A general purpose grade with a wide application range. Suitable for low to high speeds at high feeds and depths of cut,
VC907	P05-10 M20-40	C7	Turning, Boring, Threading and Grooving	Low to medium carbon steels, alloy steels, stainless steels.	Excellent wear and crater resistance. Recommended for medium speeds and high feeds.
VC927*	P10-20 M10-20 K10-20	C2	Turrning, Boring, Threading and Grooving	Alloyed Cast Irons, stainless steels, aluminum.	Provides higher edge wear resistance than VC905 at medium cutting feeds and speeds. Especially good for alloyed cast-irons.
VC928*	M20-30 K15-30	C2	Milling	Alloyed cast-irons, 300 series stainless steels, aluminum	Recommended for medium to heavy machining operations at medium speeds and high feeds.
VC929*	M10-15 K05-15	C2, C3	Turning, Boring, Milling, Threading, and Grooving	Nickel and cobalt based alloys, titanium alloys, aluminum, copper, brass, and zinc alloys.	A fine grained material for light cutting conditions. Recommended for high speed applications where flank wear resistance is required.
VC935	P15-35	C5, C6	Milling	Low carbon to medium carbon steels, heat treated alloy steels, and stainless steels.	A standard milling grade for medium to high cutting speeds, high feeds and high depths of cut under unfavorable conditions.

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Chemical Vapor Deposition (CVD), Coated Carbide

Valenite Grade	ISO Class	Industry Class	Application	Materials	Working Methods & Conditions
VN5	P10-25 M15-20	C5-C7	Turning and Boring	Steel, cast steel, malleable cast-iron, stainless steel.	A TiN coated grade for roughing and finishing. Has excellent crater and deformation resistance.
VN8	P10-30 M20-30 K10-30	C5-C7 C2-C3	Turning, Boring, Milling, Threading and Grooving	Cast-iron, steels, 300 & 400 series stainless steels, PH stainless steels.	A very well balanced TiN coated grade suitable for a broad range of applications. Has outstanding crater and impact resistance at low to high speeds.
V01	P01-30 M10-30 K01-30	C8-C5 C4-C2	Turning, Boring and Milling	Cast-iron, stainless steels, alloyed steels, carbon steels.	A composite ceramic coated grade providing maximum resistance to built-up edge. Suitable for operations ranging from roughing to finishing at medium to high speeds.
V1N	P30-45 M30-40 K25-45	C5 C1, C2	Milling, Threading and Grooving	Cast-iron, steels, high temperature exotics, 300 & 400 series stainless steels, and PH stainless steels.	A TiN coated heavy-duty grade used in severe roughing and interrupted cuts at slow speeds.
V88	P05-10 M10-30 K05-30	C6-C7 C3-C1	Turning, Boring and Milling	Cast-iron, steel, and alloyed steels.	A TiN coated grade with excellent flank wear resistance for use in applications where abrasive wear is the primary failure mode.
VX8	P15-30 M15-30 K15-30	C6-C7 C2	Turning, Boring, Threading and Grooving	Cast-iron, steel, high temperature exotics, and stainless steels.	A TiC and TiN coated grade for moderate to heavy cuts with medium to heavy feeds. Optimized for flank wear resistance.

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Figure 7.24

SpectraSystem® Coated Inserts

Valenite Grade	ISO Class	Industry Class	Application	Materials	Working Methods & Conditions
SV221	P10-25	C5, C6	Cut-off, Grooving, Turning & Slotting V-Cut Plus	Carbon steel, alloy steel, steel castings, malleable cast-iron, stainless steel and free-cutting steel.	Roughing and semi-finishing. Used in V-Cut Plus blades and toolholders.
SV231	P20-35	C5	Cut-Off, Grooving, Turning and Slotting V-Cut Plus	Stainless steel, carbon steel, and steel castings.	Roughing at medium and low speeds and high feeds. Used in V-Cut Plus blades and toolholders.
SV235	P20-45 M15-35	C5	Turning, Boring	Carbon steel, alloy steel, and stainless steel.	SV235 is the toughest of the SpectraSystem grades, engineered for maximum shock and impact resistance. It provides excellent wear resistance on all types of steel.
SV310	P01-15 M01-15 K01-15	C7,C8 C3, C4	Turning, Boring	Steels, stainless steels, iron, and some exotics.	SV310 is a high-speed finishing grade with high wear and crater resistance, high surface lubricity, and excellent wear resistance to built-up edge.
SV315	P10-30 M05-25 K01-15	C6, C7 C2, C3	Turning, Boring	Low to medium carbon steels, alloy steels, and stainless steels.	SV315 covers applications ranging from light roughing to high-speed finishing. It combines excellent wear resistance with high deformation resistance for high-speed operations.
SV325	P15-35 M10-30 K15-30	C5, C6 C1, C2	Turning, Boring	Carbon steel, alloy steel, and stainless steel.	SV325 is a general purpose grade that delivers outstanding performance in moderate roughing to semi-finishing applications, especially in interrupted cuts.

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600 Series Cermets

Valenite Grade	ISO Class	Industry Class	Application	Materials	Working Methods & Conditions
VC605	P01-05 K01-05	C8 C3-C4	Turning, Boring	Cast irons, powder metal and steels.	A high-speed finishing grade for use at low feed rates.
VC610	P01-10 K05-10	C8, C7 C3-C4	Turning, Boring	Steels, stainless steels, carbon and alloy steels, and cast-iron.	A general purpose grade recommended for high and moderate speed finishing operations. Has better wear resistance than VC671.
VC630	P10-30	C8-C6	Milling	Gray cast-iron, nodular and malleable iron-nickel based alloys, both wrought and cast aluminum.	A relatively tough grade suitable for light roughing in turning operations with a maximum depth of cut of 0.025 in. Can be used for finish milling on interrupted surfaces at high speeds.
VC671	P10-15	C7	Turning, Boring, Milling, Threading	Low to medium carbon steels, alloy steels, stainless steels.	A general purpose grade suitable for high-speed finishing at low feed rates. Somewhat tougher than VC610, but less wear resistant.

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Figure 7.26

Ceramics

Valenite Grade	ISO Class	Industry Class	Application	Materials	Working Methods & Conditions
Q6	K01-K20	C4-C2	Turning, Boring, and Milling	Cast -iron	Specifically recommended for operations ranging from heavy roughing to finishing of cast-iron. Suitable for high-speeds, heavy feeds, and interrupted cuts.
Q32	P05-15 N05-15	C7, C8	Turning, Boring, and Milling	Gray cast-iron, nickel based alloys, titanium alloys, both wrought and cast.	Cold-pressed ceramic used for light finishing operations on continuous cuts under rigid conditions.
V44	P01-10 K01-10	C7, C8 C3, C4	Turning, Boring	Cast-irons, steels, stainless steels with hardness below 35RC.	Recommended for continuous light roughing and finishing cuts on very rigid machines.

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PCBN

Valenite Grade	ISO Class	Industry Class	Application	Materials	Working Methods & Conditions
VC722	-----	-----	Turning, Boring and Milling	All cast-irons, super alloys & powder metals.	PCBN tipped inserts for general purpose roughing and finishing at high-speeds and low-speeds.
VC734	-----	-----	Turning, Boring and Milling	Martensitic cast irons (NI-HARD), high chrome irons, chilled cast-irons, cold work tool steels, nickel and iron based alloys, fully pearlitic cast-irons, case hardened steel, and martensitic stainless steels.	A solid PCBN insert intended for heavy machining and high stock removal rates. Provides excellent wear and shock resistance at high-speeds. Used without coolant.
VC721*	-----	-----	Hard Turning and Boring	Hardened steels above 60RC.	A tipped PCBN insert for a wide range of applications. Superior performance at high speeds in both continuous and interrupted cuts.

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PCD

Valenite Grade	ISO Class	Industry Class	Application	Materials	Working Methods & Conditions
VC727	-----	-----	Turning, Boring and Milling	Aluminum alloys with less than 16% silicon. Copper, fiberglass, carbon epoxies, chipboard and fiberboard.	A medium-grained, general purpose material for semi-finishing to finishing.
VC728	-----	-----	Turning, Boring and Milling	Aluminum alloys with more than 16% silicon. Non-ferrous alloys and nonmetallics.	A coarse-grained material suitable for high-speed roughing and semi-finishing operations.
VC746	-----	-----	Turning, Boring, Milling & Drilling	Aluminum, plastics, precious metal, lead alloys, other moderately abrasive materials and wood composites.	A fine-grained material for high-speed, low-feed finishing where excellent surface finishes are required.

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Recommended Starting Grades for Types of Workpiece Materials

VALENITE STARTING GRADES		STEELS		CAST IRONS		STAINLESS STL.		NON-FERROUS MATERIALS	EXOTIC MATERIALS
		<35RC	>35RC	GREY	ALLOY	200/300	400/500		
Turning & Boring	Roughing	VC5● VC27◆	----- -----	VC2● VC111◆	VC5● -----	VC2● VC101◆	VC5● -----	VC2● -----	VC2● VC101◆
	Finishing	VC7● VC5◆	VC3● VC3◆	VC3● VC29◆	VC7● VC5◆	VC29● VC2◆	VC7● VC27◆	VC3● VC29◆	VC29● VC2◆
Milling		VC7● VC35◆	----- -----	VC2● VC28◆	VC7● VC35◆	VC2● VC2◆	VC7● VC27◆	VC2● VC2◆	VC2● VC2◆
Grooving & Cut Off		VC135●	-----	VC121●	VC135●	VC121●	VC135●	VC121●	VC121●
Threading		VC7●	-----	VC2●	VC7●	VC2●	VC27●	VC2●	VC2●

Note: ● Primary choice has most wear resistance with medium impact strength or best general purpose grade. ◆ Alternate choice for more severe applications that require higher edge strength and toughness.
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Figure 7.30

Recommended Starting Grades for Types of Workpiece Materials

VALENITE STARTING GRADES		STEELS		CAST IRONS		STAINLESS STL.		NON-FERROUS MATERIALS	EXOTIC MATERIALS
		<35RC	>35RC	GREY	ALLOY	200/300	400/500		
Turning & Boring	Roughing	VC905● VC927◆	----- -----	VC902● VC927◆	VC905● VC927◆	VC901● VC928◆	VC927● VC905◆	VC902● VC927◆	VC901● VC927◆
	Finishing	VC907● VC927◆	VC929● -----	VC903● VC929◆	VC927● VC905◆	VC929● VC902◆	VC907● VC927◆	VC903● VC929◆	VC929● VC927◆
Milling		VC935● VC901◆	----- -----	VC928● VC902◆	VC935● VC905◆	VC928● -----	VC935● VC905◆	VC902● VC929◆	VC902● VC901◆
Grooving & Cut Off		VC901●	-----	VC901●	VC901●	VC901●	VC901●	VC901●	VC901●
Threading		VC905●	-----	VC902●	VC907●	VC907●	VC902●	VC90●	VC902●

Note: ● Primary choice has most wear resistance with medium impact strength or best general purpose grade. ◆ Alternate choice for more severe applications that require higher edge strength and toughness.

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Recommended Starting Grades for Types of Workpiece Materials

VALENITE STARTING GRADES		STEELS		CAST IRONS		STAINLESS STL.		NON-FERROUS MATERIALS	EXOTIC MATERIALS
		<35RC	>35RC	GREY	ALLOY	200/300	400/500		
Turning & Boring	Roughing	VN8● VN5◆	----- -----	V01● -----	V01● -----	VN8● VN5◆	VN8● VN5◆	SEE UNCOATED PVD & CERMET	VN8● -----
	Finishing	V01● VN8◆	----- -----	V01● -----	V01● -----	VN8● VN5◆	VN01● VN8◆	"	VN8● -----
Milling		V1N● V01◆	----- -----	VN5● V1N◆	VN5● V1N◆	V1N● VN8◆	V1N● VN8◆	"	V1N● V1N◆
Grooving & Cut Off		VN8●	-----	VN8●	VN8●	VN8●	VN8●	"	VN8●
Threading		VN8	-----	VN8●	VN8●	VN8●	VN25●	SEE UNCOATED PVD & CERMET	VN8●

Note: ● Primary choice has more wear resistance with medium impact strength or best general purpose grade. ◆ Alternate choice for more severe applications that require higher edge strength and toughness.
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Figure 7.32

Recommended Starting Grades for Types of Workpiece Materials

VALENITE STARTING GRADES		STEELS		CAST IRONS		STAINLESS STL.		NON-FERROUS MATERIALS	EXOTIC MATERIALS
		<35RC	>35RC	GREY	ALLOY	200/300	400/500		
Turning & Boring	Roughing	SV325● SV325◆	----- -----	SV315● SV325◆	SV315● SV325◆	SV315● SV315◆	SV325● SV325◆	SEE PVD & CERMET GRADES	SEE PVD & CERMET GRADES
	Finishing	SV310● SV315◆	----- -----	SV310● SV315◆	SV310● SV315◆	SV310● SV315◆	SV310● SV315◆		
Milling		SEE PVD/CVD/CERMET GRADES							
Grooving & Cut Off		SV231●	-----	SV221●	SV221●	SV231●	SV231●	-----	SV221●
Threading		SEE PVD/CVD/CERMET GRADES							

Note: ● Primary choice has most wear resistance with medium impact strength or best general purpose grade. ◆ Alternate choice for more severe applications that require higher edge strength and toughness.

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Recommended Starting Grades for Types of Workpiece Materials

VALENITE STARTING GRADES		STEELS		CAST IRONS		STAINLESS STL.		NON-FERROUS MATERIALS	EXOTIC MATERIALS
		<35RC	>35RC	GREY	ALLOY	200/300	400/500		
Turning & Boring	Roughing	VC610● VC671◆	----- -----	VC610● VC671◆	VC610● VC671◆	VC610● VC671◆	VC610● VC671◆	VC610● VC671◆	VC610● VC671◆
	Finishing	VC605● VC610◆	VC605● VC610◆	VC605● VC610◆	VC605● VC610◆	VC610● -----	VC610● -----	VC605● VC610◆	VC610● -----
Milling		VC630● VC610◆	----- -----	VC630● VC610◆	VC630● VC610◆	VC630● VC610◆	VC630● VC610◆	VC610● VC630◆	VC610● VC610◆
Grooving & Cut Off		SEE SPECTRA, CVD & PVD GRADES							
Threading									

Note: ● Primary choice has most wear resistance with medium impact strength or best general purpose grade. ◆ Alternate choice for more severe applications that require higher edge strength and toughness.
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Recommended Starting Grades for Types of Workpiece Materials

VALENITE STARTING GRADES		STEELS		CAST IRONS		STAINLESS STL.		NON-FERROUS MATERIALS	EXOTIC MATERIALS
		<35RC	>35RC	GREY	ALLOY	200/300	400/500		
Turning & Boring	Roughing	VC610● VC671◆	----- -----	VC610● VC671◆	VC610● VC671◆	VC610● VC671◆	VC610● VC671◆	VC610● VC671◆	VC610● VC671◆
	Finishing	VC605● VC610◆	VC605● VC610◆	VC605● VC610◆	VC605● VC610◆	VC610● -----	VC610● -----	VC605● VC610◆	VC610● -----
Milling		VC630● VC610◆	----- -----	VC630● VC610◆	VC630● VC610◆	VC630● VC610◆	VC630● VC610◆	VC610● VC630◆	VC610● VC610◆
Grooving & Cut Off		SEE SPECTRA, CVD & PVD GRADES							
Threading									

Note: ● Primary choice has most wear resistance with medium impact strength or best general purpose grade. ◆ Alternate choice for more severe applications that require higher edge strength and toughness.

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Recommended Starting Grades for Types of Workpiece Materials

VALENITE STARTING GRADES		STEELS		CAST IRONS		STAINLESS STL.		NON-FERROUS MATERIALS	EXOTIC MATERIALS
		<35RC	>35RC	GREY	ALLOY	200/300	400/500		
Turning & Boring	Roughing	VC722● VC721◆	----- -----	VC734● VC722◆	VC734● VC722◆	VC772● VC734◆	VC772● VC734◆	VC778● VC727◆	VC772● VC101◆
	Finishing	----- VC722◆	----- -----	VC734● VC722◆	VC734● VC722◆	VC722● -----	VC722● -----	VC746● VC746◆	VC722● VC722◆
Milling		VC722● -----	----- -----	VC734● VC722◆	VC734● VC722◆	VC722● -----	VC722● -----	VC728● -----	VC722● -----
Grooving & Cut Off		SEE SPECTRA/PVD/CERMET GRADES							
Threading		VC722●	-----	VC722●	VC722●	VC722●	VC722●	VC727●	VC722●

Note: ● Primary choice has most wear resistance with medium impact strength or best general purpose grade. ◆ Alternate choice for more severe applications that require higher edge strength and toughness.
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Figure 7.36

ROUGHING CHIPBREAKERS

TYPE	STYLE	D.O.C. In. (mm)	FEED RANGE ipr (mm/rev)	DESCRIPTION
3C		.050 to .300 (1.25-7.50)	.012 -.036 (0,30 - 0,90)	3C chipbreakers provide a neutral rake angle with land for high edge strength in medium duty applications on a wide range of materials. Recommended for interrupted cuts and heavy operations.
DC		.050 to .400 (1.25 - 10.00)	.010 - .043 (0,25 - 1,10)	DC chipbreakers provide for extremely heavy duty applications using a neutral rake with land for greater edge strength. Recommended for machining of steels and other materials
VI		.050 to .400 (1,25 - 10,00)	.010 - .043 (0,25 - 1,10)	VI chipbreakers provide for extremely heavy duty applications using a neutral rake with land for greater strength. Recommended for machining of steels and other materials.
GR		.080 to .400 (2,00 - 10,00)	.014 - .038 (0,35 - 0,95)	GR chipbreakers have a variable land and double step primary/secondary chipbreaker island to provide strength in heavy cuts. Recommended for interrupted cuts and heavy operations.
HS		.125 to .500 (3,12 - 12,50)	.020 - .055 (0,50 - 1,40)	HS chipbreaker provides positive cutting action for reduced cutting force and significantly less chatter in this application range. Recommended for high-feed machining on all types of metals.

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GENERAL PURPOSE CHIPBREAKERS

TYPE	STYLE	D.O.C. In. (mm)	FEED RANGE ipr (mm/rev)	DESCRIPTION
2B		.005 to .025 (0,12 - 0,62)	.005 - .025 (0,12 - 0,62)	2B chipbreakers provide a positive shear angle geometry for light to medium duty machining conditions in all types of steels. Recommended for general purpose use.
E		.050 to .200 (1,25 - 5,00)	.006 - .022 (0,15 - 0,55)	E chipbreakers provide a low positive rake angle with land for high edge strength in medium duty applications on a wide range of materials. Recommended for general purpose use on all types of steel.
ER/EL		.050 to .200 (1,25 - 5,00)	.007 - .022 (0,17 - 0,55)	The POS/NEG chipbreakers provide excellent chip control in the medium duty application ranges using a high positive shear angle. Recommended for machining of steels and other materials.
LM		.025 to .200 (0,62 - 5,00)	.007 - .022 (0,17 - 0,55)	LM chipbreakers provide excellent chip control with low cutting forces and very free cutting action over a broad range of light duty applications. Recommended for light-duty use on carbon, alloy and stainless steels.
GM		.050 to .250 (1,25 - 6,25)	.010 - .024 (0,25 - 0,60)	GM chipbreakers feature a neutral land with shear secondary angle for a near optimum combination of roughness and edge strength. Recommended for general purpose use on all types of metal.
2M		.005 to .075 (0,12 - 1,87)	.003 - .025 (0,07 - 0,62)	2M chipbreakers are specifically designed to control chips using a combination of high positive, radial and axial rake angles. Recommended for low carbon steels, and high ductility materials.
2N		.076 to .635 (1,9 - 15,87)	.010 - .025 (0,25 - 0,62)	2N is designed to provide superior chip control on a round geometry for bi-directional contouring operations. The 2N design allows for 360 degree indexing with no change in performance on medium to high feed applications.
1W		.010 to .025 (0,25 - 0,62)	.006 - .022 (0,15 - 0,55)	1W is an excellent choice for thin-walled fabricated parts and shaft turning operations where high cutting pressures can cause chatter. For work-hardened materials.

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Figure 7.38

FINISHING CHIPBREAKERS

TYPE	STYLE	D.O.C. In. (mm)	FEED RANGE ipr (mm/rev)	DESCRIPTION
LF		.005 to .080 (0,12 - 2,00)	.002 - .012 (0,05 - 0,30)	LF chipbreakers are engineered for light finishing operations at high speeds in the 0.002 to 0.012 ipr (0,05mm to 0,3mm) feed range at depths of cut between 0.005 & 0.080" (0,12mm to 2,03mm)
GF		.010 to .125 (0,25 - 3,12)	.006 - .016 (0,15 - 0,40)	GF chipbreakers provide low cutting forces with good chip control and excellent surface finishes at low feed rates and depths of cut. Recommended for light feed finishing and profiling applications.
FM		.010 to .090 (0,25 - 2,25)	.006 - .013 (0,15 - 0,32)	Light duty Pos/neg inserts provide excellent chip control in light feed ranges using high positive shear angles. Recommended for machining of steels and other materials.
6G		.002 to .004 (0,05 - 1,00)	.002 - .012 (0,05 - 0,30)	6G chipbreakers provide excellent chip control in light finishing operations. Recommended for finishing steels and cast-iron.
6K		.012 to .118 (0,30 - 2,95)	.002 - .012 (0,05 - 0,30)	6K chipbreakers combined with the performance of cermets provide for efficient chip control in finishing and light machining operations. Recommended for finishing steels & cast-iron.
7K		.010 to .080 (0,25 - 2,00)	.002 - .012 (0,05 - 0,30)	7K chipbreakers provide positive cutting action in light finishing operations at moderate to high speeds. Recommended for finishing steels and cast iron.
2T		.010 to .150 (0,25 - 3,57)	.003 - .017 (0,07 - 0,42)	2T chipbreakers provide a combination of medium and high positive rake angles for optimum chip control in light duty applications. Recommended for Inconel, stainless steel, copper and aluminum.

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POSITIVE CHIPBREAKERS

TYPE	STYLE	D.O.C. In. (mm)	FEED RANGE ipr (mm/rev)	DESCRIPTION
1A		.010 to .150 (0,25 - 3,75)	.005 - .013 (0,12 - 0,32)	1A chipbreakers provide positive shear angle cutting action for reduced cutting forces in light duty operations. Recommended for low carbon steels, non-ferrous and high-temperature alloys.
2A		.005 to .060 (0,12 - 1,50)	.0025 - .011 (0,06 - 0,27)	2A chipbreakers provide positive shear angle cutting action for reduced cutting forces in light duty operations. Recommended for low carbon steels, non-ferrous and high-temperature alloys.

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Primary Selection by Workpiece Material

AREA								
	2	INSERT MATERIAL	-------- CVD COATED INSERTS-- ---------- UNCOATED INSERTS-------CVD COATED INSERTS----UNCOATED INSERTS ---------- PVD COATED INSERTS---------- --------- CERMET INSERTS------- ---------- DIAMOND INSERTS---------- --CERAMIC INS. ---------CERAMIC INSERTS------- --CERMET INS.--					
	1	WORK-PIECE MATERIAL	STEELS 400 series s/s Carbon Steels Alloy Steels Tool Steels	IRONS Grey Ductile/ Nodular	ALUMINUM High Silicon (Automotive)	ALUMINUM Low Silicon (Aircraft)	NON-FERROUS Copper Brass Other	STAINLESS STEELS 300 Series PH Series	HIGH-TEMP. ALLOYS Nickel Base Iron Base Cobalt Base Titanium-Alloys
	3	VALCOOL CUTTING FLUID	----------TURN TECH &VNT-800----------AEROTECH---- ----------VNT-800----- ----------AEROTECH---------- ----------VNT-900---------- ----------VNT-910---------- ----------VNT-900------- ----------VNT-920---------- ----------VNT-910----------						

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Secondary Cutting Fluid Selection by Other Criteria

AREA	CRITERIA	PRODUCT TYPE					CONDITIONS	
		SYNTHETIC	SEMI - SYNTHETIC	HYBRID	SOLUBLE - OIL	STRAIGHT OIL	HARD WATER	CHLORINE FREE
4	VALCOOL CUTTING FLUID	VNT-900	AEROTECH	TURN TECH		(VNT-LT)	VNT-700	AEROTECH
		VNT-910		VNT-800			VNT-800	VNT-700
		VNT-920					VNT-900	VNT-900
		(VNT-LT)					VNT-910	VNT-910
							VNT-920	VNT-920

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Valenite Standard Grade Designations

Material Group	Material Type		Available Grades
Carbide	Uncoated		VC2, VC3, VC5, VC6, VC7, VC8, VC27, VC28, VC29, VC35M, VC101, VC111, VC121, VC135
	CVD Coated		V1N, V88, VN5, VN8, V01, VX8
	SpectraSystem PVD Coated (900 Series)		VC901, VC902, VC903, VC905, VC907, VC927, VC928, VC929, VC935
	SpectraSystem Coated (200 & 300 Series)		SV210, SV221, SV230, SV231, SV235, SV310, SV315, SV325
High Performance Materials	Cermet (600 Series)		VC605, VC610, VC630, VC671, VC673
	Ceramic	Silicon Nitride	Q6
		Aluminum Oxide	Q32
	Polycrystaline (700 Series)	PCBN	VC721, VC722, VC734
		PCD	VC706, VC725, VC726, VC727, VC728, VC746

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VALCOOL® EASY SELECTION CHART

By Material Being Cut — **By Operation**

STEELS	IRONS	ALUMINUM	ALUMINUM	NON-FERROUS	STAINLESS STEEL	HIGH-TEMP ALLOY	GRINDING	MACHINING
400 SERIES STAINLESS CARBON STEELS ALLOY STEELS TOOL STEELS	GREY DUCTILE NODULAR	HIGH SILICON (AUTOMOTIVE)	LOW SILICON (AIRCRAFT)	COPPER BRASS OTHER	300 SERIES PH SERIES	NICKEL BASE IRON BASE COBALT BASE TITANIUM BASE	VNT-920 VNT-800 TURN TECH VNT-700 VNT-910	VNT-800 TURN TECH VNT-700 AEROTECH VNT-910 VNT-900 VNT-920
VNT-800 TURN TECH VNT-910 VNT-700	VNT-800 TURN TECH VNT-920 VNT-700	VNT-800 TURN TECH AEROTECH VNT-700	VNT-800 TURN TECH AEROTECH VNT-700	VNT-800 TURN TECH AEROTECH VNT-700	VNT-800 TURN TECH VNT-910 VNT-900	VNT-800 TURN TECH VNT-910 VNT-900		

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TURNING GRADE COMPARISON CHART

VALCOOL (■)	ISO/ANSI CLASS	VALENITE		GREENLEAF		ISCAR		KENNAMETAL		MITSUBISHI		NEWCOMER	
		COATED	UNCTD.	COATED	UNCTD.	COATED	UNCTD.	COATED	UNCTD.	COATED	UNCTD.	COATED	UNCTD.
TURN TECH VNT-800	P50 P-40 C5	SV325 SV235 V1N	VC111 VC56	Ti5 Ti6 GA56	G01 G50	IC635 IC656	IC54	KC850 KC9045 KC9040 KC935	K2S				N52 N55
VNT-900	P40 P30 C5-C6	SV325 SV315 SV225	VC27 VC5	GA6 GA60	G53 G54 G52	IC825	IC50 IC70	KC935 KC9025	K2S	U6025 U625	Uti20T	NP1000	N50 N60
VNT-910	P30 P20 C6-C7	SV315 SV310	VC7	G1+	G60 G74 G70	IC805 IC815	IC78 IC60T	KC9010	K45	U6010 U610		NN55 NA02 NN6	N70 N72
	P20 P10 C7-C8	SV310 V01	VC7			IC848		KC9010	K45	U505 U66	STi10T		N80 N93 N95
	P10 P01 C8	V01 SV310	VC8				IC80T	KC9010		U505 U66			
TURN TECH VNT-800	M40 M30	V1N VC901 SV235	VC111 VC101	GA56 GA60	G50	IC635		KC9045 KC9040 KC250	K2S	U625			N10 N52 N55
VNT-900	M30 M20	SV325 SV225 VC901 SV315	VC101 VC29	Ti5 GA60 GA56	G10 G52 G60	IC825		KC850 KC935 KC730 KC9025	K21 K313 K68	U6025 US735 U625 UP35N	UTi20T	NP1000	N22 N25 N30
VNT-910	M15 M10	SV315 VC929 SV310	VC29 VC2	G1+ Ti6 GA6	GO2 G74	IC825		KC9010 KC910 KC730				NT25	N20 N60
VNT-800	K40 K30 C1	V1N SV325	VC111 VC101		GO1M	IC635	IC28	KC9040 KC250 KC850	K1				N10
	K30 K20 C1-C2	SV325 SV315 VC928	VC28 VC2 VC29	GA56	G10 GO2M	IC848 IC805		KC250 KC9025 KC720	K6 K40 K313	U6025 UP20M U625			N22 N20
VNT-920	K20 K10 C2-C3	SV315 SV310 VC929	VC29 VC3	G1+ GA2 Ti2 Ti6	GO2 G30 G23	IC848 IC805	IC20 IC2 IC28	KC9010 KC990 KC730	K68 K6	U6010 U610	Uti20T HTi10T	NT25 NT2	N30 N20
	K05 K01 C4	SV310 V01	VC3 VC29	G2	G40 G25		IC4	KC9010 KC910		U66	HTi05T		N40 N20

K = Grey cast-iron; M = Stainless steel, Nodular iron; P = Steels. (■) Use VNT-800 in harder water. © Valenite Inc.

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TURNING GRADE COMPARISON CHART (Continued)

ISO/ANSI CLASS	VALENITE		RTW		SANDVIK		SUMITOMO		TELEDYNE		TOSHIBA		V. R. WESSON	
	COATED	UNCTD.	COATED	UNCTD.	COATED	UNCTD.	COATED	UNCTD.	COATED	UNCTD.	COATED	UNCTD.	COATED	UNCTD.
P50-P40 C5	SV325 SV235 V1N	VC111 VC56	955 755	CY55	GC4035 GC235 GC435	S6		ST40E	TC41	T04	T370 T823	TX40	643 623 650 653	VR79 VR77
P40-P30 C5-C6	SV325 SV315 SV225	VC27 VC5	925 716	CY16 CY17	GC4025 GC1025 GC425	S4	AC25 AC2000	ST30E	MP51	T14 T12	T822 T813 T803	UX30 TX25	630 663	VR75 VR73
P30-P20 C6-C7	SV315 SV310	VC7	918 715 714		GC4015 GC415	S4	AC2000 AC10 AC15	ST20E	MP37 MP26	T25 SD5 T24	T801 T802 T823	TX20 TX10	680	
P20-P10 C7-C8	SV310 V01	VC7		CY31 CY14	GC3015 GC4015	S1P	AC05 AC10	ST10P	MP15	T25	T822		690	
P10-P01 C8	V01 SV310	VC8			GC3015		AC05	ST10P	MP15	SD3	T5010		690	
M40-M30	V1N VC901 SV235	VC111 VC101			GC235 GC435 GC4035		AC720						650 653	
M30-M20	SV325 SV225 VC901 SV315	VC101 VC29	925		GC4025 GC425	S6 H13A	AC720 AC25	G10E			T802 T370 T812 T803 T823		630 653 650 663	RAMET1 VR82 VR73
M15-M10	SV315 VC929 SV310	VC29 VC2	918 718		GC4015 GC4025 GC425 GC415	H10A H13A	AC10 AC2000 AC15	G10E	MP37		T802T8 03 T812 T813		630 680 633	VR52 VR65
K40-K30 C1	V1N SV325	VC111 VC101		CQ12	GC4035 GC435						T370	G3		RAMET1
K30-K20 C1-C2	SV325 SV315 VC928	VC28 VC2 VC29	925	CQ2	GC4035 GC4025 GC435	H10A H13A	AC10G AC25 AC2000		MP21	H17 H91	T813	G2 G2F	633 660	
K20-K10 C2-C3	SV315 SV310 VC929	VC29 VC3	918	CQ4 CQ3	GC4015 GC3015 GC415	H10A H1P H13A H20	AC105 AC10G	G10E H10E	HN+ C46	HTA H21 HA H36		TH10 G1F	630 680 690	2A5 VR82 2A7
K05-K01 C4	SV310 V01	VC3 VC29			GC3015	H1P	AC05 AC105		HN+	SD3 HF	T5010	TH03		VR52 VR65

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Figure 7.45 Insert cutting tool comparison chart.

TURNING CHIPBREAKER COMPARISON CHART

C'BRKR. TYPE	VALENITE	GREENLEAF	ISCAR	KENNAMT'L	MITSUBISHI	NEWCOMER	RTW	SANDVIK	SUMITOMO	TELEDYNE	TOSHIBA	VR. WESSON
LIGHT FINISHING	LF		PP	MG-UF	F, PK		FF	QF	EFP, ENK EFK		01, 11	
GENERAL FINISHING	GF	FF	NF	MP-K MG-K	SA, SH, C		FF	PF, MF -23	EUP, ENS EFM, EUU	2B, 2M, 3F	27, SS	
LIGHT MACHINING	LM	GP	NP	MS GG-P MG-P	MA	S	GP	PM, -61	ENG, ENJ EFJ, ENZ	3G	32, 32X 28, SA	MF, MS
GENERAL MACHINING	GM	MR	TNM, NG	MG-P MG-MG	MS, D	MN	GA	PM, QM	EMU, EMX	3S	33, 37 38, 21	W
GENERAL ROUGHING	GR	HR		MG	GH	PG	GR	MR		4T, 4U 4W, SW, SX		MH
HIGH-FEED ROUGHING	HS	MM	NM	MM, MM-M MM-P MM-MR, MH	HA		HR	PR, QR, HR	EHP, ENP		57, 65 81, 82	
POSITIVE INSERT C'BRKRS.	1A, 2A FL FH		14, 19, 16 MR, GR	MR, MT, GM GT, GT-HP	MR, SQ, MQ	MR, MT	CF1	UF, UM, UR	EFK, ENK EFM, EMF	1K, 2C 2K, 3K	23, 24	MP, MM, GP
POS-NEG C'BRKRS.	FM, MM MP, 2B, 1W		MM, MS-12 MP-14	MP, GP MS, GS	MP, KMS 1G, PK	MZ, MX F, Y	MP, MX MZ, MS	MP	Q, T	MP-3D	P, S	

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Figure 7.46 Insert cutting tool comparison chart.

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Machining insert material types. The following describes currently available machining insert materials and their applications. This information, together with the machining charts and remedies for cutting or machining problems appearing in this section of the *Handbook,* will enable you to select the proper type of insert and insert material for specific machining applications and requirements. (Information courtesy of Valenite, Inc.)

Uncoated carbide. This tungsten carbide–based material with a cobalt binder, frequently alloyed with combinations of titanium and tantalum carbides, is available in all ANSI and International Standards Organization (ISO) grade groups for metal-cutting applications. These inserts cut all materials, including irons, steels, and superalloys; aluminum and brass alloys; and nonmetallics, including plastics, phenolics, and composites. Applications range from heavy roughing to finishing on almost all machining operations.

CVD-coated carbide. This insert material is available in a complete range of grades, with substrates engineered for maximum compatibility with coatings. Coatings include

- Titanium carbide (TiC)
- Titanium nitride (TiN)
- Composite ceramic (Al_2O_3)
- Multiple coatings

These grades are excellent for machining most materials, including cast irons, steels, stainless steels, and some superalloys—in turning, boring, and milling operations.

PVD-coated carbide. Inserts coated with a thin film (2 to 4 microns) of titanium nitride (TiN) by physical vapor deposition (PVD) are characterized by good wear resistance, low coefficient of friction, and resistance to edge buildup. PVD (TiN) coatings are applied at temperatures substantially below those used for chemical vapor deposition (CVD), the process used most commonly for coating carbide cutting tools. The result is less reaction with the substrate and thus better edge-strength retention. Low coating temperatures allow greater control over deposition rate and result in closer tolerances and more grain-size control.

Silicon nitride. This hot-pressed monolithic silicon nitride–based ceramic is designed to do one thing exceptionally well—cut cast

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iron materials. It offers outstanding toughness and thermal resistance and handles turning, boring, and milling operations at speeds from 350 to 5000 sfm. Because Quantum 6 retains its hardness, toughness, and abrasion resistance at elevated temperatures, it can provide excellent tool life at these speeds.

PCBN. Polycrystalline cubic boron nitride (PCBN) inserts, available in both tipped and solid forms, are designed to machine ferrous workpiece materials in the 40- to 70-RC range. PCBN is significantly harder than cemented carbide or ceramic materials and is the only material that combines a high degree of toughness with exceptional hot-hardness. PCBN excels in turning of hardened steels, chilled and gray cast irons, and Ni-Hard materials.

PCD. Polycrystalline diamond (PCD) inserts provide premium performance when cutting highly abrasive, low-tensile-strength, nonferrous, nonmetallic, and aluminum composite work materials. The exceptionally hard, wear-resistant diamond cutting tip retains its sharpness even in demanding applications, running up to 7500 sfm and beyond. As a result, PCD inserts provide up to 100 times the tool life of carbide. Excellent for roughing and high-speed finishing on turning, boring, and milling operations.

SpectraSystem coated carbide. Spectra-coated carbide grades represent the latest development in advanced coating technology and offer unique substrates for turning and milling. This combination allows Spectra-coated inserts to provide increased productivity at higher cutting speeds with greater wear resistance over a broad range of applications and work materials. Applications range from heavy roughing to precision finishing on work materials that include all steels, stainless steels, many superalloys, and alloyed cast irons.

Cermet. This type includes composite titanium carbide– and titanium nitride–based materials designed for light roughing to high-speed finishing in turning, boring, and milling operations. These grades show excellent results on steels, stainless steels, cast irons, and aluminum. They are capable of running at moderate to high speeds and are best used with light feeds and depths of cut. They feature excellent abrasion resistance and thermal properties, as well as lubricity for crater resistance.

Ceramic. Quantum 32 (Q32) is a metal oxide composite with edge strength well suited for materials with hardness from 35 to 65 RC,

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including some hardened steels, irons, and some superalloys. Quantum 32 is available in a wide range of shapes, sizes, and geometries.

Material characteristics and insert tool application considerations. The following listings provide extensive information relating to insert tool machining of various materials. Each item describes machining characteristics for the specific material, notes various conditions that may be encountered while machining it, and provides remedies for correcting the conditions or problems listed. See Fig. 7.75 for milling recommendations on different milling operations.

Low-carbon and free-machining steels. 1100 series, 1008, 1010, 1018, and 1200 series, leaded steels, and steels with free-machining additives.

Material characteristics: Low-carbon, soft and gummy; difficult chip control; torn finish is common; high-speed capability. Free machining, easy to machine; high-speed capability; high depths of cut achievable; easy chip control.

Tool-application considerations

Condition: Torn finish (built-up edge)

Remedy: Increase speed; use cermets; use PVD-coated grade with sharp edge; use positive-rake inserts; increase coolant concentration.

Condition: Difficult chip control

Remedy: Increase speed; change lead angle to redirect chip away from workpiece.

Condition: Burrs and sharp edges

Remedy: Change cutting path; use PVD-coated grade with sharp edge; use positive-rake or high-positive-rake inserts.

Medium/high-carbon steels and alloy steels. 1045, 1085, 1541, 1561, 1572, and 4000 series, 4300 series, 5100 series, 8600 series, 52100, and 300M.

Material characteristics: Higher chrome, nickel, and molybdenum content, work hardening; higher carbon content, abrasive but achieves surface finish easier; higher nickel content, more carbon and alloy, more difficult to machine.

Tool-application considerations

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Condition: Crater wear

Remedy: Use aluminum oxide–coated grade; reduce speed; use more free-cutting chip control; use cermets; increase coolant pressure; reduce feed.

Condition: Flank wear

Remedy: Use TiC/alumina ceramics; use aluminum oxide–coated grade; increase feed; increase coolant concentration; increase depth of cut.

Condition: Thermal deformation

Remedy: Use more wear-resistant grade; reduce speed; reduce feed.

Tool steels

Material characteristics: Abrasive, work hardening, and tough; hard-to-break chips.

Tool-application considerations

Condition: Flank wear

Remedy: Use aluminum oxide–coated grade; reduce speed; increase feed.

Condition: Crater wear

Remedy: Use aluminum oxide–coated grade; use cermets; reduce speed; reduce feed.

Condition: Dull surface finish

Remedy: Increase speed; use positive-rake inserts (PVD-coated); use cermets; increase coolant concentration.

Gray cast iron. Gray, classes 20, 25, 30, 45, and 60, high tensile.

Material characteristics: Abrasive, potential scale and inclusions, tendency to break out during exit from cut, potential for chatter on thin-wall sections.

Tool-application considerations

Condition: Excessive edge wear

Remedy: Use harder grade or aluminum oxide–coated grades; use ceramics; increase feed to reduce in-cut time.

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Condition: Chipping

Remedy: Increase lead angle; use stronger grade; use prehoned inserts or inserts with edge preparation.

Condition: Workpiece breakout

Remedy: Use sharp inserts or PVD-coated grades; use lower feed rate during exit; increase speed; increase lead angle; use positive geometries for finish cuts.

Condition: Workpiece chatter

Remedy: Use sharp inserts or PVD-coated grades; use positive rake inserts; increase lead angle; increase feed to stabilize workpiece.

Ductile cast iron. Nodular/ductile, malleable.

Material characteristics: Abrasive, difficult to machine, good surface finishes difficult to achieve.

Tool-application considerations

Condition: Edge wear

Remedy: Use harder grades; apply aluminum oxide–coated grades; consider ceramics and cermets for finishing; increase feed to reduce in-cut time.

Condition: Crater wear

Remedy: Apply aluminum oxide–coated grades; apply geometries that are free-cutting; lower speed (sfpm).

Condition: Torn or dull surface finish

Remedy: Apply ceramics, cermets, or PVDs at higher speeds and lower feeds; increase lead angle; increase coolant concentration.

Hardened irons

Material characteristics: Highly abrasive, high cutting forces.

Tool-application considerations

Condition: Excessive edge wear

Remedy: Apply alumina-based ceramics or cubic boron nitride (CBN) grades; feed above 0.004 ipr; increase lead angles or use round inserts; check coolant application.

Condition: Catastrophic breakage

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Remedy: Increase lead angles or use round inserts; use large nose radii; repair toolholder; reduce feeds.

Austenitic stainless steels. 200 and 300 series.

Material characteristics: Work hardens rapidly; small depths of cut are difficult; usually abrasive rather than hard; tough and stringy chips.

Tool-application considerations

Condition: Depth-of-cut notch

Remedy: Increase lead angle; use tougher grade; feed over 0.005 ipr.

Condition: Built-up edge

Remedy: Increase speed; use cermets; use positive-rake inserts (PVD-coated).

Condition: Workpiece glazing

Remedy: Increase depth of cut; reduce nose radius; use sharp PVD-coated grades.

Condition: Dull surface finish

Remedy: Increase speed; reduce feed; increase positive rake.

Ferritic/martensitic stainless steels. 400 series and precipitation-hardening PH grades.

Material characteristics: Brittle, stringy chips; high cutting forces; high work hardening (especially PH stainless grades).

Tool-application considerations

Condition: Built-up edge

Remedy: Increase speed; use cermets; use positive-rake inserts (PVD-coated); increase coolant concentration.

Condition: Workpiece glazing

Remedy: Increase depth of cut; reduce nose radius; use positive-rake inserts (PVD-coated); increase coolant concentration.

Condition: Depth-of-cut notch

Remedy: Increase lead angle; use tougher grade; feed over 0.005 ipr.

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Condition: Torn or dull surface finish

Remedy: Increase speed; reduce feed; use positive-rake inserts (PVD-coated); increase coolant concentration.

High-temperature alloys. Iron, nickel, and cobalt base.

Material characteristics: Relatively poor tool life; small depths of cut are difficult; work hardens rapidly; usually abrasive rather than hard; tough and stringy chips.

Tool-application considerations

Condition: Depth-of-cut notch

Remedy: Increase lead angle; use tougher grade; use 0.015-in or greater depth of cut; feed over 0.005 ipr; increase coolant concentration.

Condition: Built-up edge

Remedy: Increase speed; change cutting tool material; use positive-rake inserts (PVD-coated); do not overrun cutting edge; increase coolant concentration.

Condition: Workpiece glazing

Remedy: Increase depth of cut; increase feed rate; reduce nose radius; use positive-rake inserts (PVD-coated).

Condition: Torn or dull surface finish

Remedy: Increase speed; reduce feed; use positive-rake inserts (PVD-coated); increase coolant concentration.

Titanium alloys. Pure, alpha, alpha-beta, and beta alloys.

Material characteristics: Relatively poor tool life; chips tend to gall and weld to cutting edge; requires lower cutting speeds than steels of equal hardness; usually abrasive; tough and stringy; low thermal conductivity.

Tool-application considerations

Condition: Depth-of-cut notch

Remedy: Increase lead angle; use 0.015-in or greater depth of cut; remove embrittled surface from mill stock; feed over 0.005 ipr; increase coolant concentration.

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Condition: Built-up edge

Remedy: Keep a sharp edge; use positive-rake inserts (PVD-coated); increase coolant concentration.

Condition: Workpiece glazing

Remedy: Increase depth of cut; reduce nose radius; use positive-rake inserts (PVD-coated); index cutting edge.

Condition: Torn or dull surface finish

Remedy: Index cutting edge; reduce feed; use positive-rake inserts (PVD-coated); increase speed; increase coolant concentration.

High-silicon and free-machining aluminum

Free-machining aluminum: 1000, 1100, 1200, and 1300 series; 2011 through 2024 series; 3000 series. 1050 to 1350 are almost pure. 2011 to 2024: 2024 is popular (screw-machine products, aircraft parts); contains copper, manganese, and magnesium.

Material characteristics: Soft and gummy

Tool-application considerations

Condition: Built-up edge

Remedy: Increase speed; use positive-rake inserts (PVD-coated); use coolants designed for machining aluminum; J polish top of insert.

Condition: Torn or dull surface finish

Remedy: Increase speed; reduce feed; use positive-rake inserts (PVD-coated); use coolant designed for aluminum; use polycrystalline diamond tools; J polish top of insert.

High-silicon aluminum: 4000, 5000, 6000, and 7000 series (7000 series uses zinc, zirconium, and titanium as alloying additives). 4000 series: Contains silicon for heat resistance and wear. 5000 series: Contains chromium. 6000 series: 6061 typical, contains silicon, copper, magnesium, and chromium. 7000 series: Contains copper, magnesium, chromium, and zinc (aircraft parts).

Material characteristics: Abrasive and tough.

Tool-application considerations

Condition: Edge wear

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Remedy: Use coated grade; use polycrystalline diamond tools; increase coolant concentration.

Condition: Built-up edge/surface finish

Remedy: Increase speed; increase coolant concentration.

Nonferrous alloys and nonmetallics

Nonferrous metals: Free-machining and high-strength copper alloys, brass, zinc, and magnesium

Material characteristics: Easily machined; high machining speeds; positive chip control with magnesium to reduce fire hazards.

Caution: Fire hazard is present when machining magnesium at high speeds.

Nonmetallics: Nylons, acrylics, phenolics, and resin materials.

Material characteristics: Easily machined; high machining speeds; machine with polycrystalline diamonds whenever possible; center height of cutting is important.

Tool-application considerations

Condition: Built-up edge

Remedy: Increase speed; use positive-rake inserts; J polish top of inserts.

Condition: Poor surface finish

Remedy: Increase speed; use polycrystalline diamond inserts; use positive-rake inserts; J polish top of inserts; use positive chip control.

7.1.9 Grades of cutting inserts (for use with Figs. 7.14 through 7.44)

The insert grades described in the charts are those of Valenite, Inc., with the figures also listing the ANSI and ISO equivalents as reference.

Selection of speed, feed, and depth of cut. Use the preceding speed, feed, and depth-of-cut figures as a basis for these choices. Useful tool life is influenced most by cutting speed. The feed rate is the

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next most influential factor in tool life, followed by the depth of cut (doc).

When the depth of cut exceeds approximately 10 times the feed rate, a further increase in depth of cut has little effect on tool life. In selecting the cutting conditions for a turning or boring operation, the first step is to select the depth of cut, followed by selection of the feed rate and then the cutting speed. Use the preceding horsepower/kilowatt equations to determine the approximate power requirements for a particular depth of cut, feed rate, and cutting speed to see if the machine can handle the power required. You also may use one of the cutting tool manufacturers' machining calculators to determine appropriate machining parameters. Many production and tooling engineers prefer to use the calculators provided by the manufacturers who supply their cutting tools, together with production trial runs on any particular part, in determining the final machining parameters.

Select the heaviest depth of cut and feed rate that the machine can sustain, considering its horsepower or kilowatt rating, in conjunction with the required surface finish desired on the workpiece.

Relation of speed to feed. The following general rules apply to most turning and boring operations:

- If the tool shows a built-up edge, increase feed or increase speed.
- If the tool shows excessive cratering, reduce feed or reduce speed.
- If the tool shows excessive edge wear, increase feed or reduce speed.

Caution: The productivity settings from the machining calculators and any handbook speed and feed tables are suggestions and guides only. A safety hazard may exist if the user calculates or uses a table-selected machine setting without also considering the machine power and the condition, size, strength, and rigidity of the workpiece, machine, and cutting tools.

Turning, boring, and threading inserts. Figure 7.47*a* shows a sample of some of the typical cutting inserts available today. The versatile 80° diamond inserts are shown in the center area of the figure (two inserts) to the left and right of the lower center triangle. Various types and styles of tool holders for the inserts are produced by the insert manufacturers to hold the disposable inserts rigidly in position during the cutting operation. Figure 7.47*b* shows samples of typical turning and boring toolholders, and Fig. 7.47*c* shows a modern

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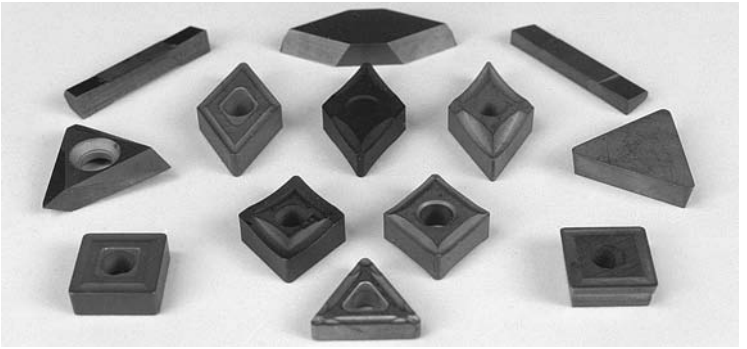
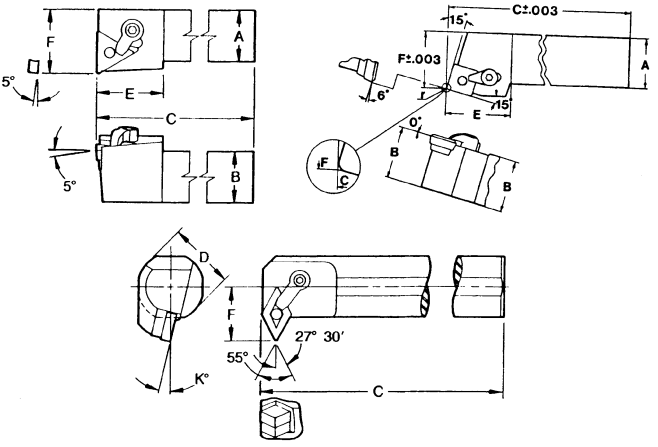


(a)



(b)

(c)

Figure 7.47 Cutting inserts (*a*); insert tool holders (*b*); a convertible insert and tool holder (*c*).

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tool holder with a multipurpose, double-ended cutting insert. With the one insert, finishing, facing, and cutoff operations may be performed according to the orientation angle of the tool holder in relation to the workpiece.

7.1.10 ANSI and ISO identification systems for turning, boring, and milling inserts

Removable turning, boring, and milling inserts are identified and specified according to the American National Standards Institute (ANSI) and the International Standards Organization (ISO) systems shown in Figs. 7.48 and 7.49, respectively. Sample drawings of various types of inserts are shown in Fig. 7.50. The identification code is listed at the top right of each insert and may be referenced back to the ANSI identification system (see Fig. 7.48).

7.1.11 Thread turning

Thread-turning inserts are available in different styles or types for turning external and internal thread systems such as UN series, 60° metric, Whitworth (BSW), Acme, ISO, American buttress, etc. Figure 7.51 shows some of the typical thread-cutting inserts.

The defining dimensions and forms for various thread systems are shown in Fig. 7.52 with indications of their normal industrial uses. The dimensions in the figure are in U.S. Customary and metric systems as indicated. In all parts of the figure, P = pitch, reciprocal of threads per inch (for U.S. Customary) or millimeters (for metric).

Figure 7.52*a* defines the ISO thread system: M (metric) and UN (unified national). Typical uses: all branches of the mechanical industries. Figure 7.52*b* defines the UNJ thread system (controlled-root radii). Typical uses: aerospace industries. Figure 7.52*c* defines the Whitworth system (BSW). Typical uses: fittings and pipe couplings for water, sewer, and gas lines; presently replaced by ISO system. Figure 7.52*d* defines the American buttress system, 7° face. Typical uses: machine design. Figure 7.52*e* defines the American national pipe thread (NPT) system. Typical uses: pipe threads, fittings, and couplings. Figure 7.52*f* defines the British standard pipe thread (BSPT) system. Typical uses: pipe thread for water, gas, and steam lines. Figure 7.52*g* defines the Acme thread system, 29°. Typical uses: mechanical industries for motion-transmission screws.

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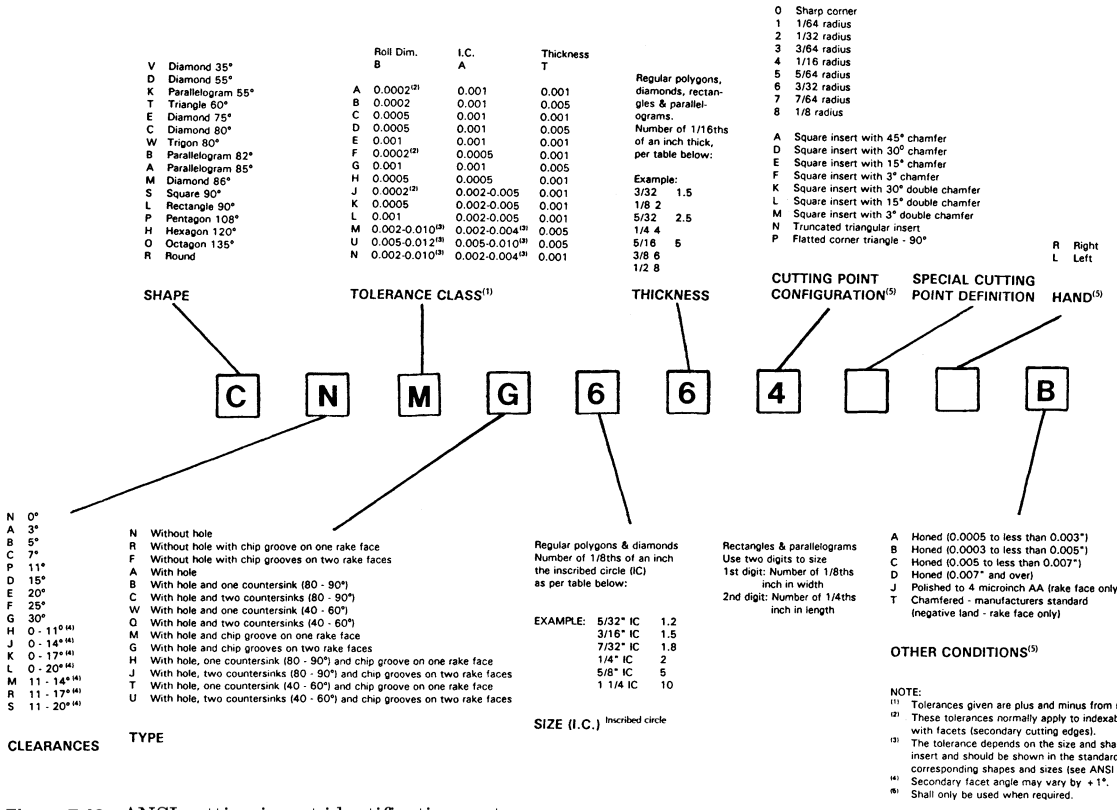
V Diamond 35°
D Diamond 55°
K Parallelogram 55°
T Triangle 60°
E Diamond 75°
C Diamond 80°
W Trigon 80°
B Parallelogram 82°
A Parallelogram 85°
M Diamond 86°
S Square 90°
L Rectangle 90°
P Pentagon 108°
H Hexagon 120°
O Octagon 135°
R Round
SHAPE
Roll Dim. B
I.C. A
Thickness T
A 0.0002(2) 0.001 0.001
B 0.0002 0.001 0.005
C 0.0005 0.001 0.001
D 0.0005 0.001 0.005
E 0.001 0.001 0.001
F 0.0002(2) 0.0005 0.001
G 0.001 0.001 0.005
H 0.0005 0.0005 0.001
J 0.0002(2) 0.002-0.005 0.001
K 0.0005 0.002-0.005 0.001
L 0.001 0.002-0.005 0.001
M 0.002-0.010(3) 0.002-0.004(3) 0.005
U 0.005-0.012(3) 0.005-0.010(3) 0.005
N 0.002-0.010(3) 0.002-0.004(3) 0.001
TOLERANCE CLASS(1)
Regular polygons, diamonds, rectangles & parallelograms. Number of 1/16ths of an inch thick, per table below:
Example:
3/32 1.5
1/8 2
5/32 2.5
1/4 4
5/16 5
3/8 6
1/2 8
THICKNESS
0 Sharp corner
1 1/64 radius
2 1/32 radius
3 3/64 radius
4 1/16 radius
5 5/64 radius
6 3/32 radius
7 7/64 radius
8 1/8 radius
A Square insert with 45° chamfer
D Square insert with 30° chamfer
E Square insert with 15° chamfer
F Square insert with 3° chamfer
K Square insert with 30° double chamfer
L Square insert with 15° double chamfer
M Square insert with 3° double chamfer
N Truncated triangular insert
P Flatted corner triangle - 90°
CUTTING POINT CONFIGURATION(5)
SPECIAL CUTTING POINT DEFINITION
R Right
L Left
HAND(5)
C N M G 6 6 4 B
N 0°
A 3°
B 5°
C 7°
P 11°
D 15°
E 20°
F 25°
G 30°
H 0 - 11° (4)
J 0 - 14° (4)
K 0 - 17° (4)
L 0 - 20° (4)
M 11 - 14° (4)
R 11 - 17° (4)
S 11 - 20° (4)
CLEARANCES
N Without hole
R Without hole with chip groove on one rake face
F Without hole with chip grooves on two rake faces
A With hole
B With hole and one countersink (80 - 90°)
C With hole and two countersinks (80 - 90°)
W With hole and one countersink (40 - 60°)
Q With hole and two countersinks (40 - 60°)
M With hole and chip groove on one rake face
G With hole and chip grooves on two rake faces
H With hole, one countersink (80 - 90°) and chip groove on one rake face
J With hole, two countersinks (80 - 90°) and chip grooves on two rake faces
T With hole, one countersink (40 - 60°) and chip groove on one rake face
U With hole, two countersinks (40 - 60°) and chip grooves on two rake faces
TYPE
Regular polygons & diamonds
Number of 1/8ths of an inch the inscribed circle (IC) as per table below:
EXAMPLE: 5/32" IC 1.2
3/16" IC 1.5
7/32" IC 1.8
1/4" IC 2
5/8" IC 5
1 1/4 IC 10
SIZE (I.C.) Inscribed circle
Rectangles & parallelograms
Use two digits to size
1st digit: Number of 1/8ths inch in width
2nd digit: Number of 1/4ths inch in length
A Honed (0.0005 to less than 0.003")
B Honed (0.0003 to less than 0.005")
C Honed (0.005 to less than 0.007")
D Honed (0.007" and over)
J Polished to 4 microinch AA (rake face only)
T Chamfered - manufacturers standard (negative land - rake face only)
OTHER CONDITIONS(5)
NOTE:
(1) Tolerances given are plus and minus from nominal.
(2) These tolerances normally apply to indexable inserts with facets (secondary cutting edges).
(3) The tolerance depends on the size and shape of the insert and should be shown in the standards for the corresponding shapes and sizes (see ANSI B94.25).
(4) Secondary facet angle may vary by + 1°.
(5) Shall only be used when required.

Figure 7.48 ANSI cutting insert identification system.

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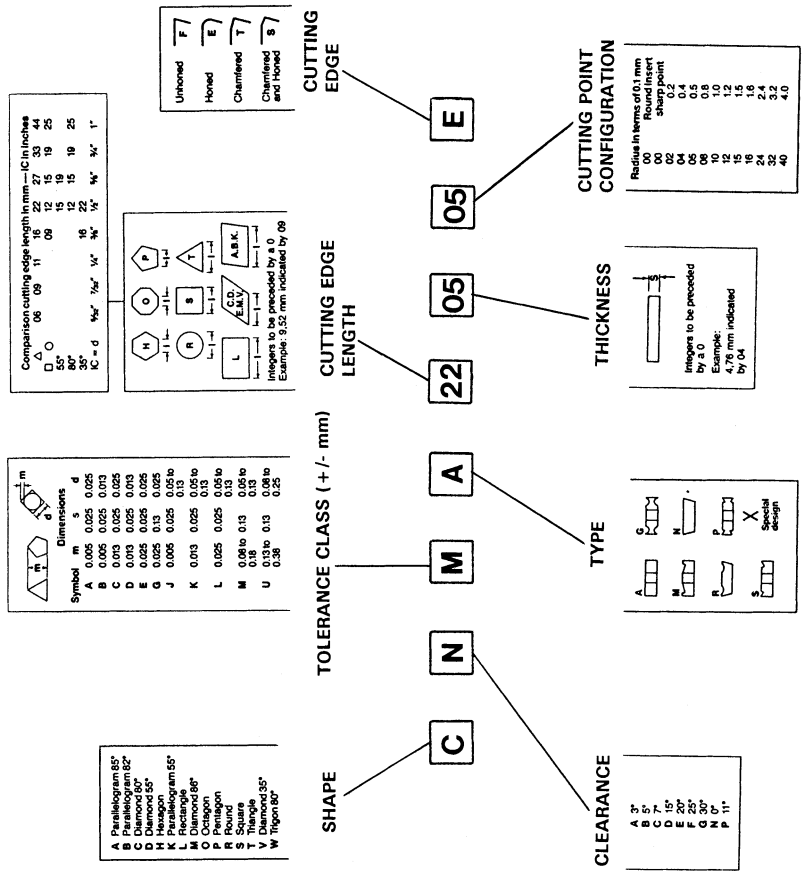

Figure 7.49 ISO cutting insert identification system.

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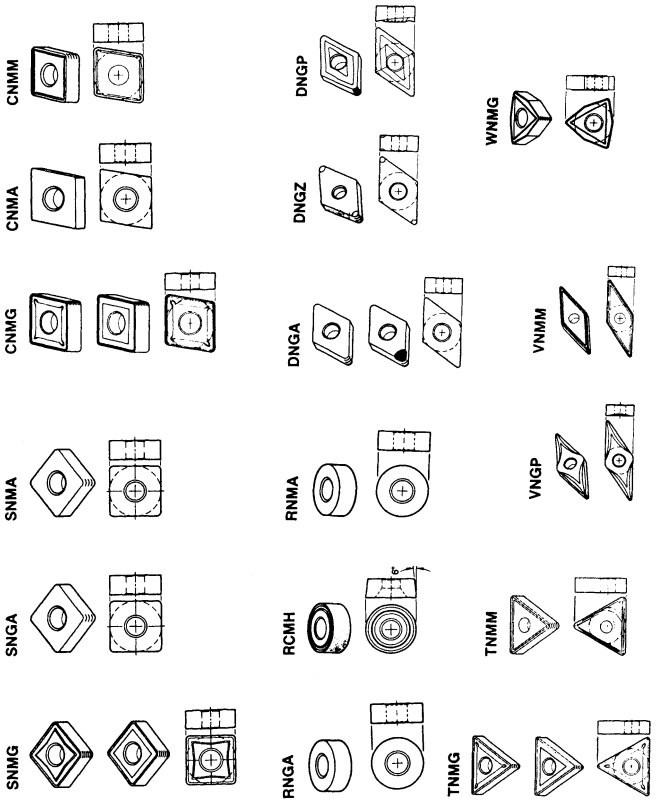

Figure 7.50 Sample inserts with identification codes.

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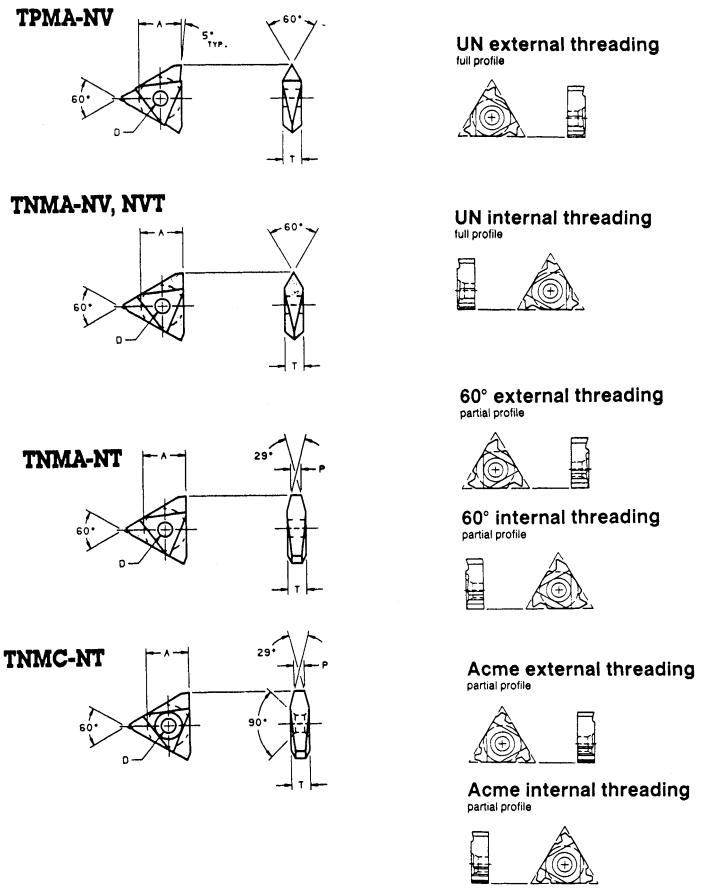

Figure 7.51 Sample inserts and threat-cutting inserts.

Figure 7.52*h* defines the stub Acme thread system, 29°. Typical uses: same as Acme, but used where normal Acme thread is too deep. Figure 7.52*i* defines the API 1:6 tapered-thread system. Typical uses: petroleum industries. Figure 7.52*j* defines the TR DIN 103 thread system. Typical uses: mechanical industries for motion-transmission screws. Figure 7.52*k* defines the RD DIN 405 (round) thread system. Typical uses: pipe couplings and fittings in the fire-protection and food industries.

(Text continued on page 409.)

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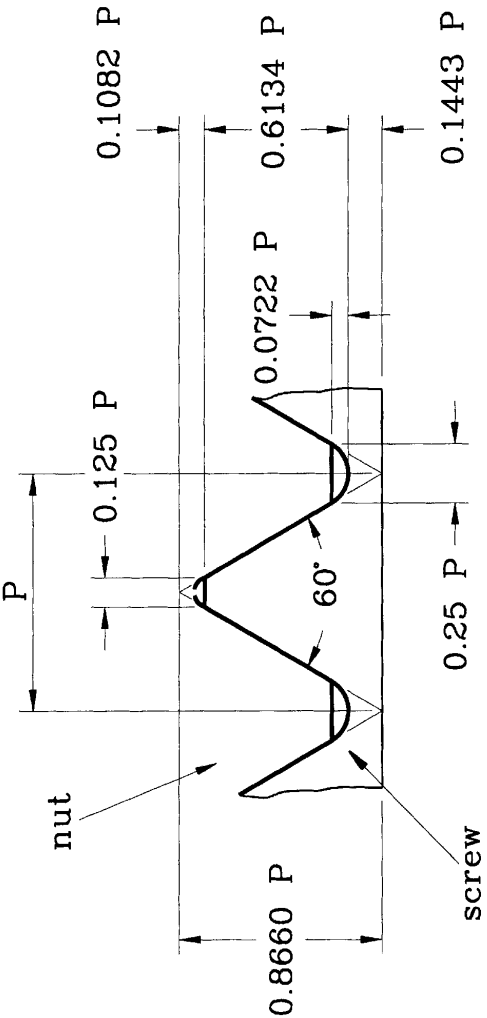

(a) ISO - M (Metric)
(UN) (Unified National)

Figure 7.52 Thread systems and dimensional geometry.

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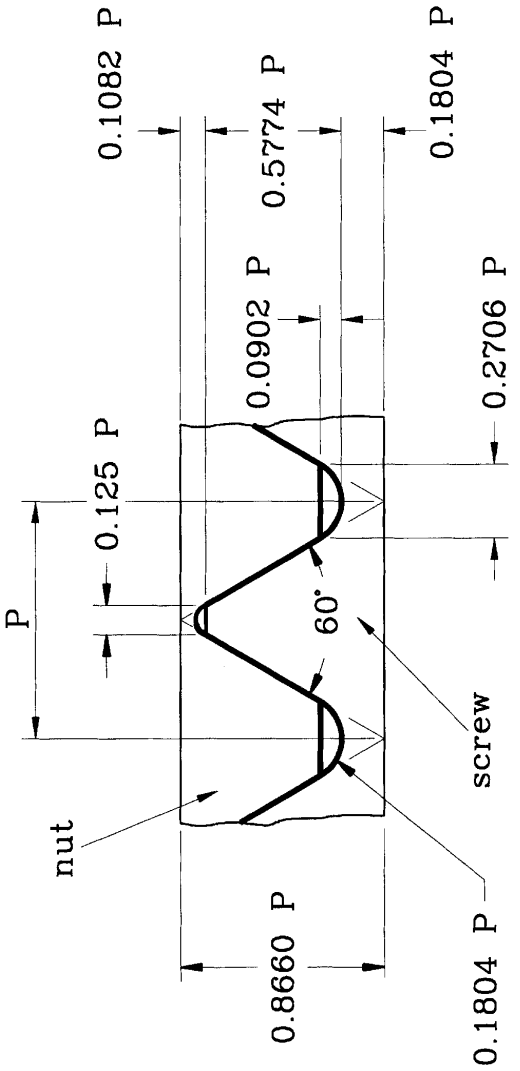

(b) UNJ
(Controlled root radii)

Figure 7.52 *(Continued)*

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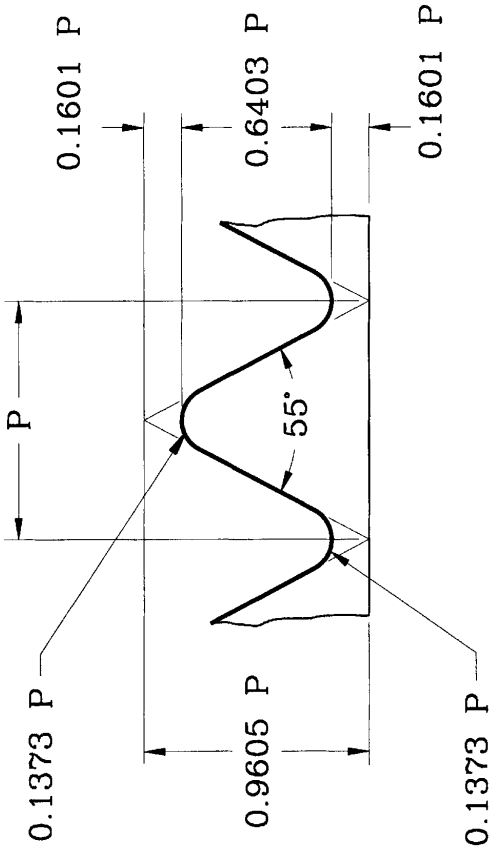

(c) Whitworth (BSW)

Figure 7.52 *(Continued)*

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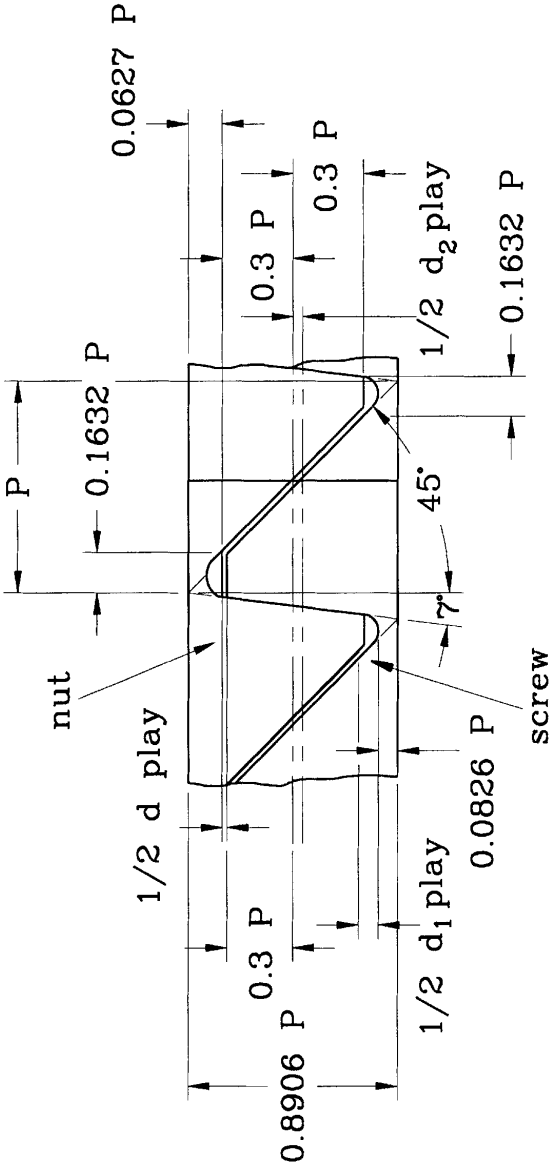

(d) American Buttress (7° face)

Figure 7.52 *(Continued)*

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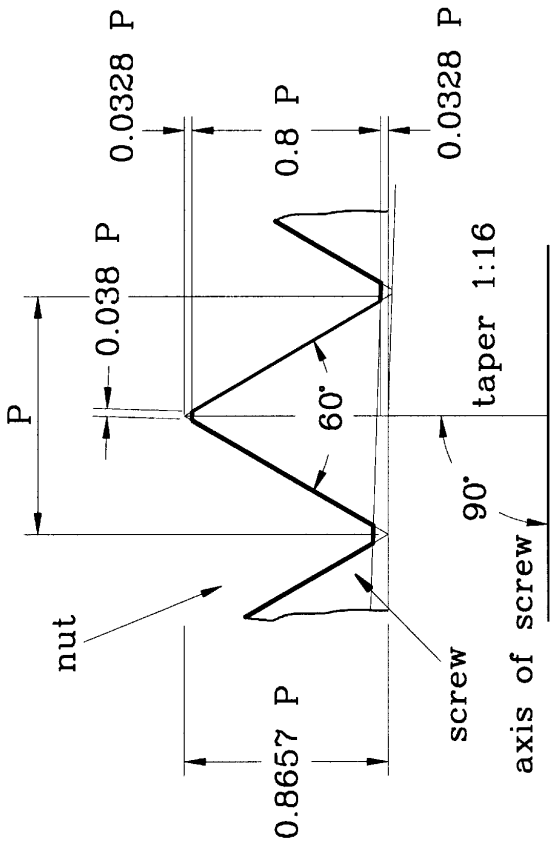

(e) NPT
(American National Pipe Thread)

Figure 7.52 *(Continued)*

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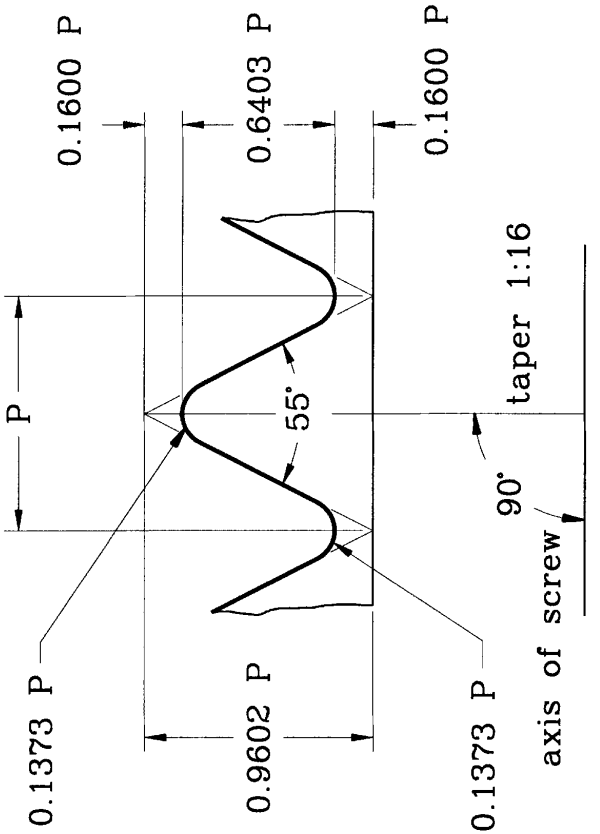

(f) BSPT
(British Standard Pipe Thread)

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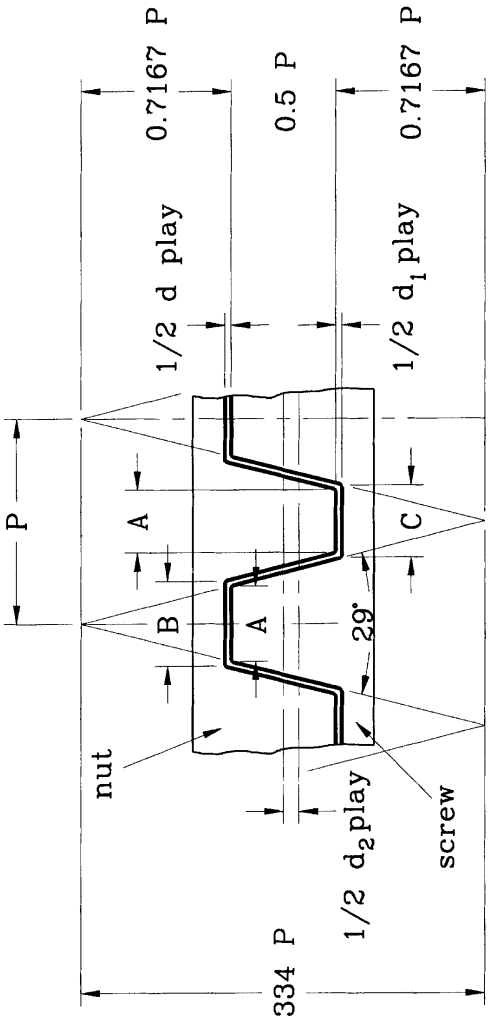

(g) Acme (29°)

Figure 7.52 *(Continued)*

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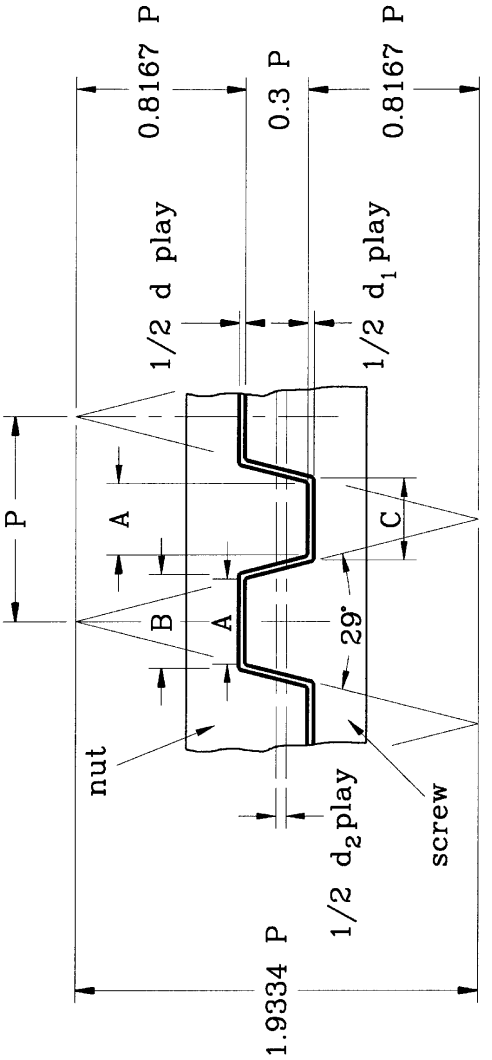

A=0.4224 P
B=0.4224 P−0.259 x d play
C=0.4224 P−0.259 (d_1 play−d_2 play)

(h) Acme Stub (29°)

Figure 7.52 *(Continued)*

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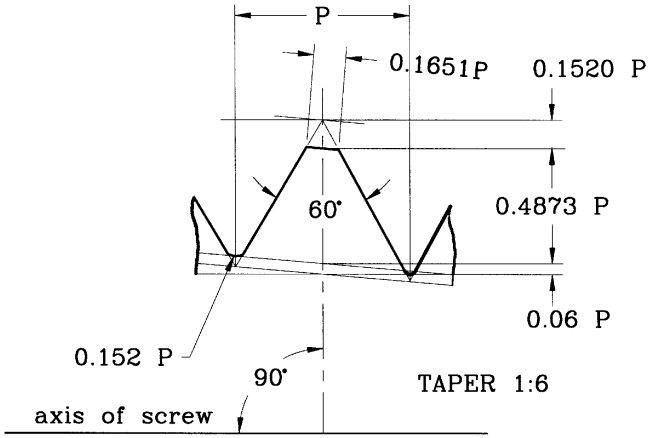
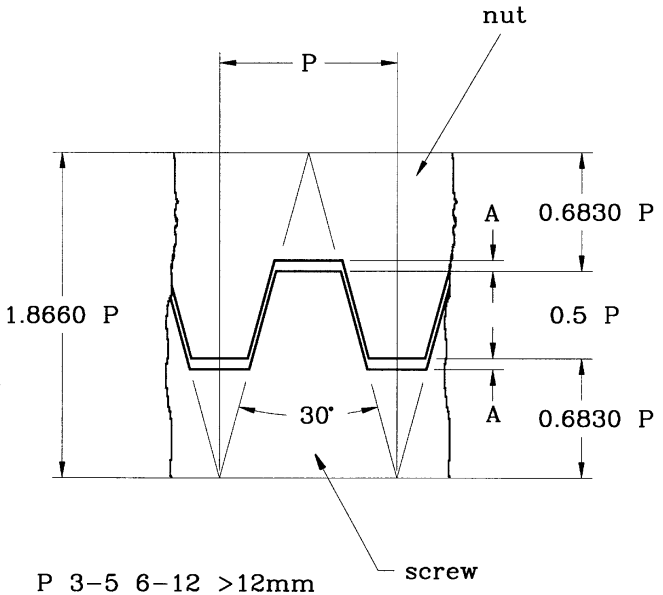


(i) API
Taper: 1:6 (V-0.38"R)



(j) TR DIN 103

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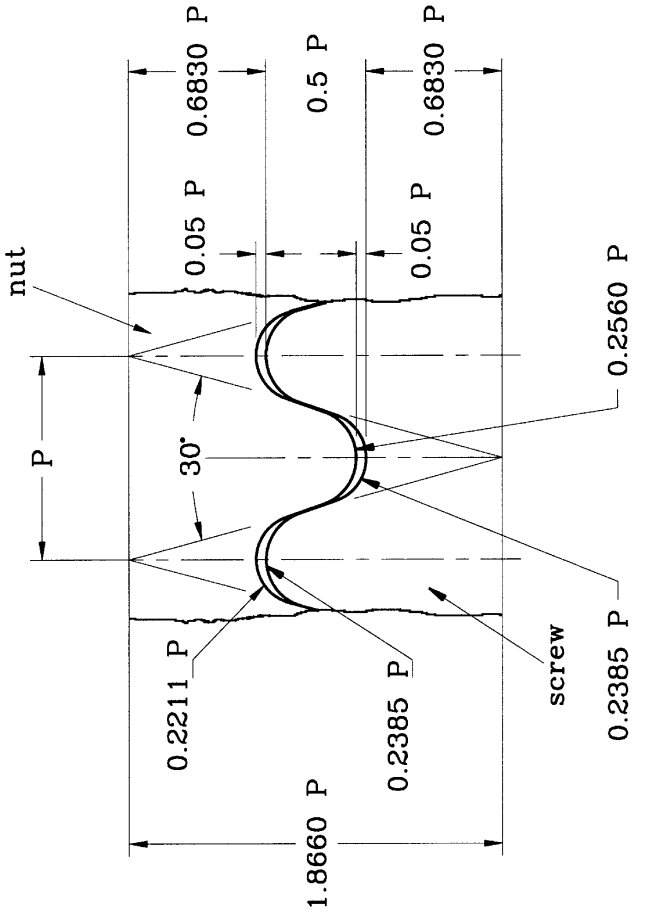

(k) RD DIN 405 (Round)

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Threading operations. Prior to cutting (turning) any particular thread, the following should be determined:

- Machining toward the spindle (standard helix)
- Machining away from the spindle (reverse helix)
- Helix angle (see following equation)
- Insert and toolholder
- Insert grade
- Speed (sfpm)
- Number of thread passes
- Method of in-feed

Calculating the thread helix angle. To calculate the helix angle of a given thread system, use the following simple equation (see Fig. 7.53):

$$\tan \alpha = \frac{p}{\pi D_e}$$

where $\tan \alpha$ = natural tangent of the helix angle, degrees
D_e = effective diameter of thread, in or mm
π = 3.1416
p = pitch of thread, in or mm

Example: Find the helix angle of a unified national coarse 0.375-16 thread.

$$p = 1/16 = 0.0625$$

(The pitch is the reciprocal of the number of threads per inch in the U.S. Customary system.)

$$D_e = 0.375 \text{ in}$$

Therefore,

$$\tan \alpha = \frac{0.0625}{3.1416 \times 0.375} = 0.05305$$

$$\arctan 0.05305 = 3.037°$$

The helix angle of any helical thread system can be found by using the preceding procedure.

Cutting procedures for external and internal threads. Figure 7.54 illustrates the methods for turning the external thread systems

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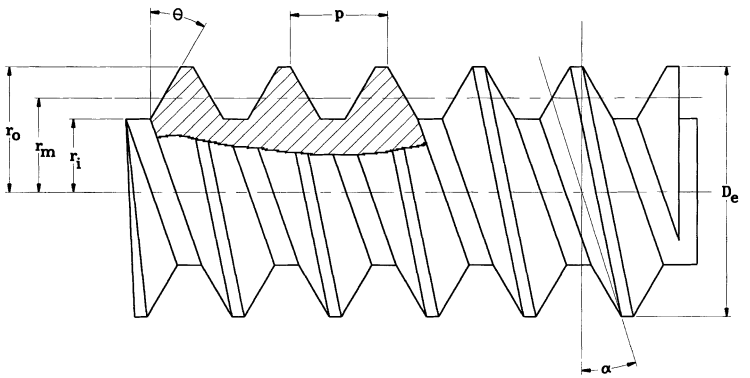

Figure 7.53 Calculating the helix angle.

(standard and reverse helix). Figure 7.55 illustrates the methods for turning the internal thread systems (standard and reverse helix).

Problems in thread cutting

Problem	Possible remedy
Burr on crest of thread	Increase surface feet per minute (rpm). Use positive rake. Use full-profile insert (NTC type).
Poor tool life	Increase surface feet per minute (rpm). Increase chip load. Use more wear-resistant tool. Increase surface feet per minute (rpm).
Built-up edge	Increase chip load. Use positive rake, sharp tool. Use coolant or increase concentration.
Torn threads on workpiece	Use neutral rake. Alter in-feed angle. Decrease chip load. Increase coolant concentration. Increase surface feet per minute (rpm).

In-feed methods for thread cutting

0° in-feed angle. When the in-feed angle is 0°, cutting occurs on both sides of the thread form, which places all the cutting edge in

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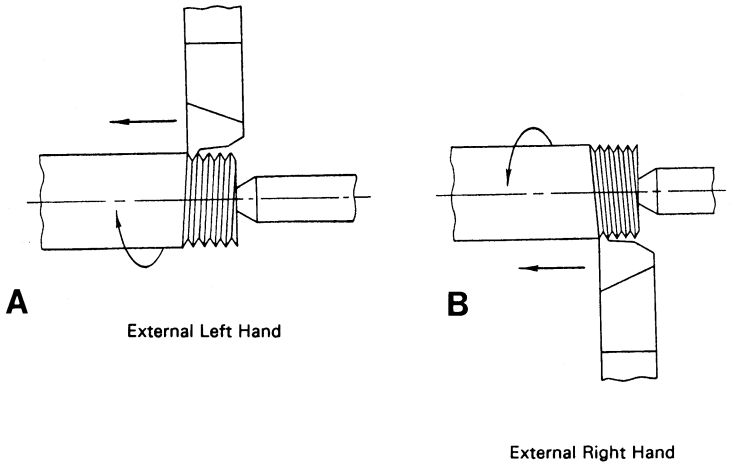

Figure 7.54 Thread-cutting procedures, external.

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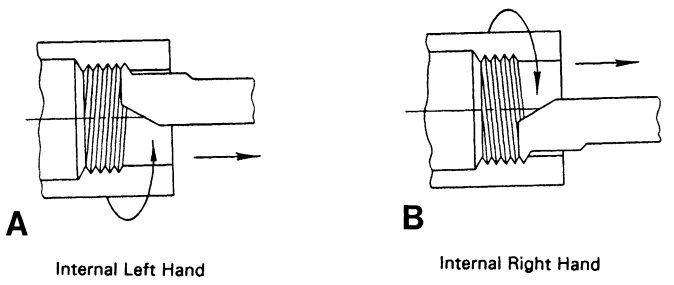

Figure 7.55 Thread-cutting procedures, internal.

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the cut and helps protect the edge from chipping. *Disadvantages:* May produce difficult-to-handle chip; the tip of the tool may chip when cutting high-tensile-strength materials; burring is increased; and chatter problems may develop.

Large in-feed angle (15° to 30°). Cutting with the leading edge of the tool produces an easy-to-handle chip, and reduced burr problems occur on the trailing edge of the tool. *Disadvantages:* Trailing edge of tool may drag and tend to chip; torn or poor surface occurs when cutting soft, gummy materials such as low-carbon steels (1020, etc.) and low-alloy aluminums or pure aluminum.

Small in-feed angle (5° to 10°). Tool cuts from both sides and is protected from chipping; chip is easy to handle. *Disadvantages:* Similar to 0° in-feed but less in magnitude because cutting forces are equalized, and chip is easy to control.

Standard thread systems and standard hardware. See Chap. 17 for ANSI standards applicable to machining and metalworking. Also see Chap. 14 on fastening and joining techniques and hardware.

7.1.12 Modern turning centers and standard lathe machine tools

The modern direct numerical control (DNC) turning center has replaced many types of older machine tools such as automatic screw machines, small turret lathes, and profiling equipment. Figure 7.56 shows a typical automatic CNC turning center.

A sample of typical parts produced on this type of machine tool is shown in Fig. 7.57. The controllers of these machines can be seen in the photographs. The spindle and coolant line can be seen near the center of the machine shown in Fig. 7.56. The bar-stock material is fed through the spindle and clamped in position for cutting by a collet-type mechanism at the spindle.

Figure 7.58 shows a typical small turret lathe used to produce small parts when the production rates do not warrant the use of a DNC turning center. Figure 7.59 shows a typical geared-head engine lathe equipped with digital readout panel used for setting the controls and movements of the machine. The digital readout panel is shown in the upper left of the photograph and reads to four decimal places (±0.0005 in). Engine lathes of this type have been the major basic machines used in the metalworking industries for

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Figure 7.56 A modern CNC turning center.

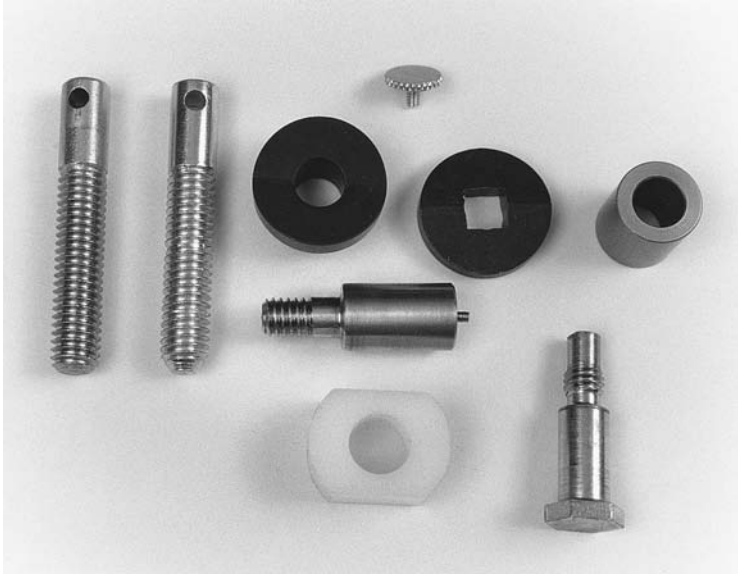

Figure 7.57 Typical CNC machined parts (turned, milled, etc.).

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Figure 7.58 A small production manual turret lathe.

Figure 7.59 Large geared-head engine lathe with digital panel.

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many years, together with the standard milling machines. It has been said often that the engine lathe can produce almost any type of detail part requiring machining when equipped with the proper accessories and auxiliary devices.

7.2 Milling

Milling is a machining process for generating machined surfaces by removing a predetermined amount of material progressively from the workpiece. The milling process employs relative motion between the workpiece and the rotating cutting tool to generate the required surfaces. In some applications the workpiece is stationary, and the cutting tool moves, whereas in others the cutting tool and the workpiece are moved in relation to each other and to the machine. A characteristic feature of the milling process is that each tooth of the cutting tool takes a portion of the stock in the form of small, individual chips.

Typical cutting tool types for milling machine operations are shown in Figs. 7.60 and 7.61.

Milling methods

- Peripheral milling (slab milling)
- Face milling and straddle milling
- End milling
- Single-piece milling
- String or "gang" milling
- Slot milling
- Profile milling
- Thread milling
- Worm milling
- Gear milling

Modern milling machines have many forms, but the most common types are shown in Fig. 7.62. The well-known and highly popular Bridgeport-type milling machine is shown in Fig. 7.63. The Bridgeport machine is often used in tool and die making operations

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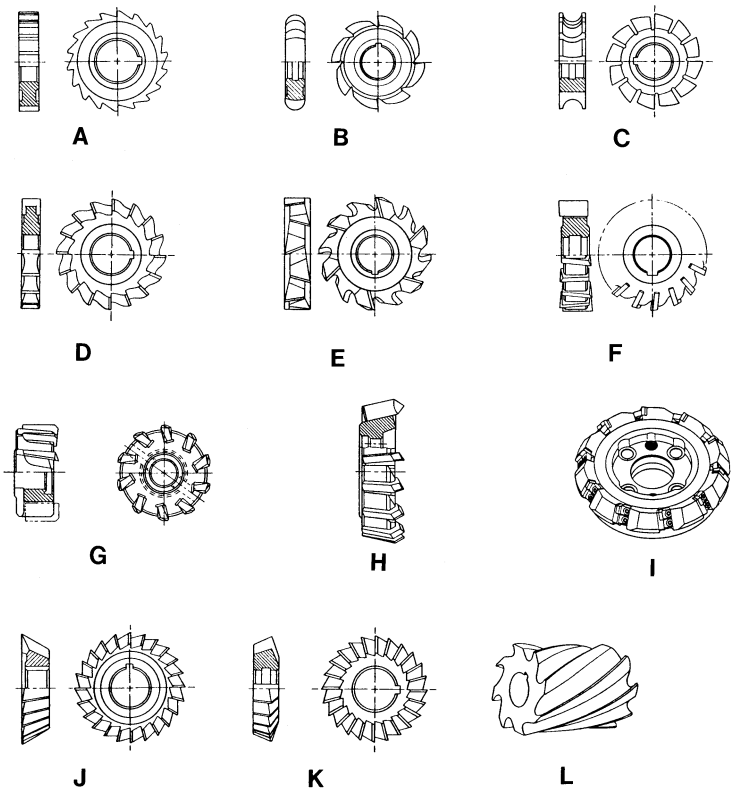

Milling Cutter Styles - High-Speed Steel and Carbide Insert

A Disk type milling cutter
B Convex half-round milling cutter
C Concave half-round milling cutter
D Three-side milling cutter
E Staggered-tooth milling cutter
F Inserted blade milling cutter
G Face milling cutter
H Face milling head
I Double-angle carbide insert milling cutter
J Single-angle milling cutter
K Double-angle milling cutter
L Left hand slab milling cutter

Figure 7.60 Typical milling cutters.

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Figure 7.61 Samples of end-milling cutters.

and in model shops, where prototype work is done. The great stability and accuracy of the Bridgeport makes this machine popular with many experienced machinists and die makers. The Bridgeport shown in Fig. 7.63 is equipped with digital sensing controls and readout panel, reading to ±0.0005 in.

A ball-end milling operation is shown in Fig. 7.64, where an aluminum alloy part is being cut on a Bridgeport-type machine. This aluminum part is being manufactured without the use of a cutting solution or coolant. Many of the better grades of aluminum alloys, such as 2024, 6061, and 7075, can be considered free-machining and often are cut without coolants and at high surface speeds (see speeds and feeds section). When cutting solutions and coolants are used for turning or milling aluminum alloys, special formulations are available and may be used (see coolants and cutting solutions section).

A large vertical milling machine is shown in Fig. 7.65. This machine is set up to straddle-mill copper alloy castings using face mills in a parallel, stacked array in order to make two cuts on two surfaces with one pass of the part through the cutters. In this application, the cast

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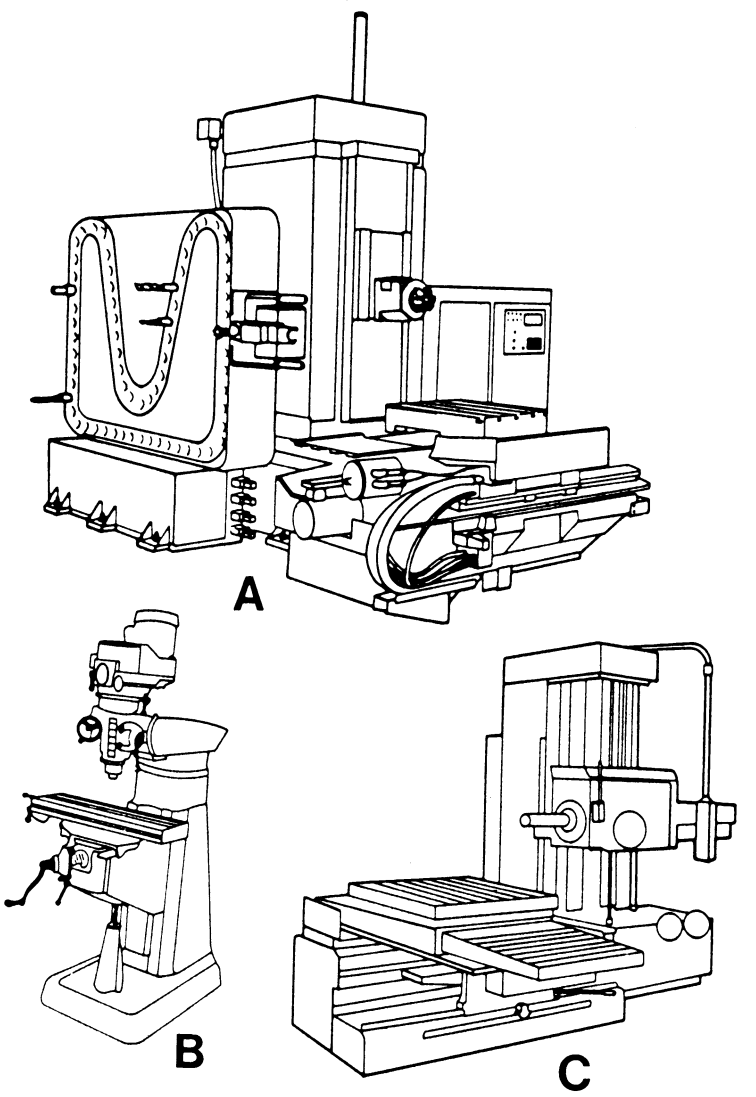

Figure 7.62 Types of milling machines.

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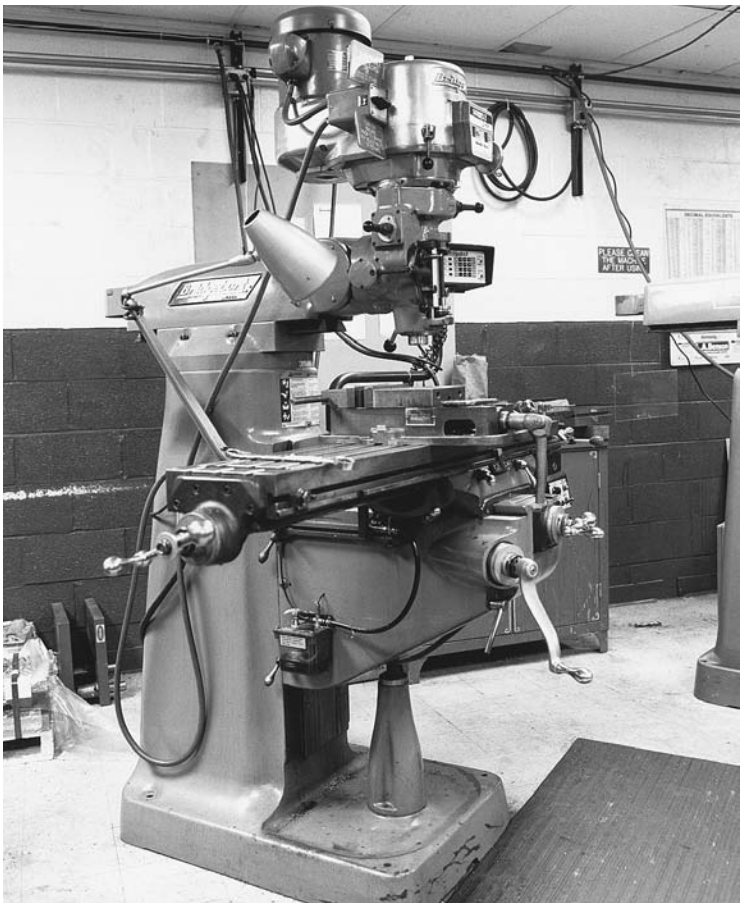
copper parts are positioned in pneumatic clamps in a "gang" or string arrangement. Many parts thus are cut in a single traverse of the horizontal table. Mass-production techniques such as these allow parts to be manufactured more quickly and at less cost. The milling cutters on this machine are of the facemill removable-carbide insert type, the inserts being made of tungsten carbide with a titanium nitride or titanium carbide coating.



(a)

Figure 7.63 (*a*) The popular Bridgeport universal milling machine. (*b*) Close-up of milling operation showing digital panel.

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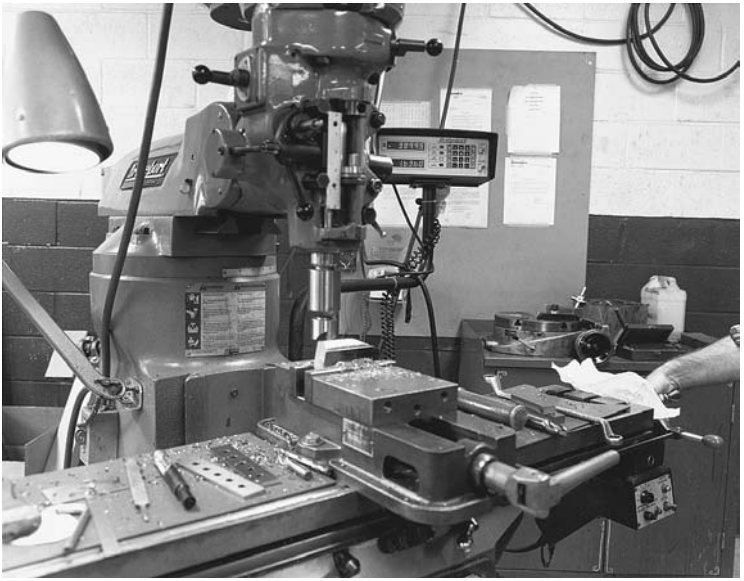

(b)

Figure 7.63 (*Continued*)

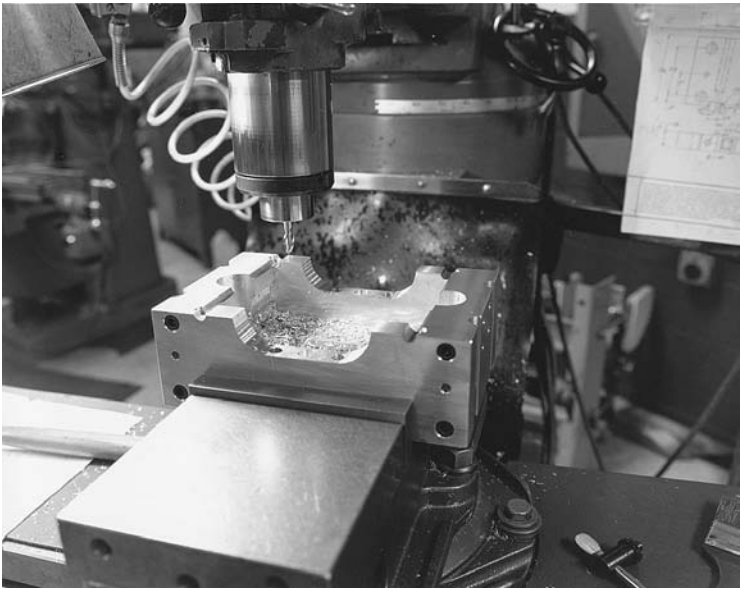

Figure 7.64 Close-up of ball-milling operation on an aluminum alloy part.

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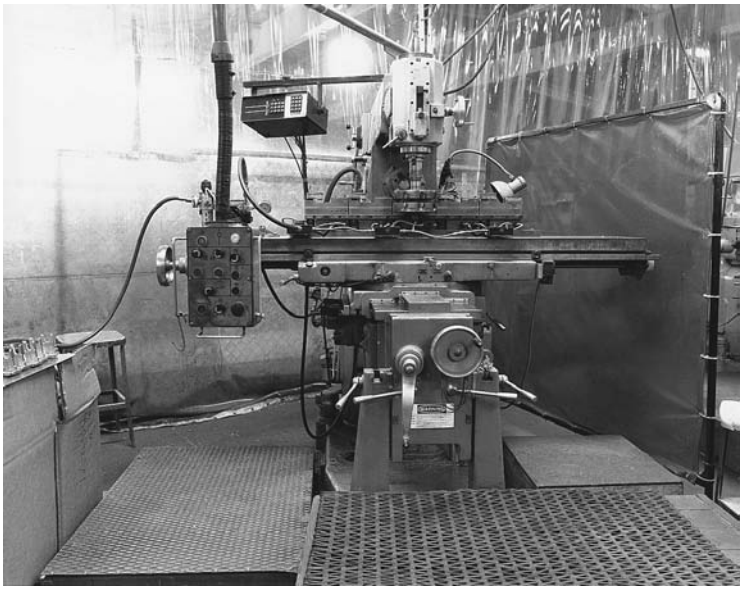

Figure 7.65 Large milling machine shown straddle-milling production parts.

The modern machining center is being used to replace the conventional milling machine in many industrial applications. Figure 7.66 shows a machining center with its control panel at the right side of the machine. Machines such as these generally cost $250,000 or more, depending on the accessories and auxiliary equipment obtained with the machine. These machines are the modern "workhorses" of industry and cannot remain idle for long periods owing to their cost. As described in Chap. 1, these machines are computer controlled and make their own tool changes automatically during ongoing machining operations. Figure 7.67 shows a typical "gang-milling" operation of aluminum cast parts that are finish bored, drilled, and then tapped while being held in a pneumatically actuated clamping fixture. The pneumatic line can be seen coming into the fixture at the lower right side of the photograph. Four coolant lines are shown directed at the machine spindle in the cutting tool location. These coolant lines move with the tool and spindle during the cutting operation. One needs to see these machines in actual operation to appreciate the great speed and accuracy with which they perform their programmed (CNC) machining functions.

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Figure 7.66 Vertical machining center in operation.

Figure 7.67 Close-up of production milling, pallet-mounted parts.

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The modern machining center may be equipped for three-, four-, or five-axis operation. The normal or common operations usually call for three-axis machining, whereas more involved machining procedures require four- or even five-axis operation. Three-axis operation consists of x and y table movements and z-axis vertical spindle movements. The four-axis operation includes the addition of spindle rotation with three-axis operation. Five-axis operation includes a horizontal fixture for rotating the workpiece on a horizontal axis at a predetermined speed (rpms), together with the functions of the four-axis machine. This allows all types of screw threads to be machined on the part and other operations such as producing a worm for worm-gear applications, segment cuts, arcs, etc. Very complex parts may be mass produced economically on a three-, four-, or five-axis machining center, all automatically, using CNC.

The control panels on these machining centers contain a microprocessor that is, in turn, controlled by a host computer, generally located in the tool or manufacturing engineering office; the host computer controls one or more machines with direct numerical control (DNC) or distributed numerical control. Various machining programs are available for writing the operational instructions sent to the controller on the machining center.

7.2.1 Milling calculations

The following calculation methods and procedures for milling operations are intended to be guidelines and not absolute because of the many variables encountered in actual practice.

Metal-removal rates. The metal-removal rate R (sometimes mrr) for all types of milling is equal to the volume of metal removed by the cutting process in a given time, usually expressed as cubic inches per minute (in^3/min). Thus

$$\mathrm{R} = WHf$$

where R = metal-removal rate, in^3/min
W = width of cut, in
H = depth of cut, in
f = feed rate, ipm (in/min)

In peripheral or slab milling, W is measured parallel to the cutter axis and H perpendicular to the axis. In face milling, W is measured perpendicular to the axis and H parallel to the axis.

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Feed rate. The speed or rate at which the workpiece moves past the cutter is the feed rate f, which is measured in inches per minute (ipm). Thus

$$f = F_t N C_{\text{rpm}}$$

where f = feed rate, ipm
F_t = feed per tooth (chip thickness), in (also called cpt)
N = number of cutter teeth
C_{rpm} = rotation of the cutter, rpm

Feed per tooth. Production rates of milled parts are directly related to the feed rate that can be used. The feed rate should be as high as possible, considering machine rigidity and power available at the cutter. To prevent overloading the machine drive motor, the allowable feed per tooth F_t may be calculated from

$$F_t = \frac{K \text{hp}_c}{N C_{\text{rpm}} W H}$$

where hp_c = horsepower available at the cutter (80 to 90 percent of motor rating); i.e., if motor nameplate states 15 hp, then the horsepower available at the cutter is 0.8 to 0.9×15 (80 to 90 percent represents motor efficiency)
K = machinability factor (see Fig. 7.68)

Other symbols are as in the preceding equation.

Figure 7.69 gives the suggested feed per tooth for milling using high-speed-steel (HSS) cutters for the various cutter types. For carbide, cermets, and ceramic tools, see the figures in the feeds and speeds section.

Cutting speed. The cutting speed of a milling cutter is the peripheral linear speed resulting from rotation of the cutter. The cutting speed is expressed in feet per minute (fpm, or ft/min) or surface feet per minute (sfpm or sfm) and is determined from

$$S = \frac{\pi D(\text{rpm})}{12}$$

where S = cutting speed, fpm or sfpm (sfpm is also termed spm)
D = outside diameter of the cutter, in
rpm = rotational speed of cutter, rpm

The required rotational speed of the cutter may be found from the following simple equation:

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(K) Factor for Various Materials

Material	K(in^3/min/(hp_c))
Cold drawn steel, SAE 1112, 1120, 1315	1.0
Forged and alloy steel, SAE 3120, 1020, 2320, 2345, 150-300 BHN	0.63 - 0.87
Alloy steel, 300 - 400 BHN	0.5
Malleable iron and cold drawn steel, SAE 6140	0.9
Cast irons:	
Soft	1.5
Medium	0.8 - 1.0
Hard	0.6 - 0.8
Stainless steel, AISI 416, free-machining	1.1
Stainless steel, austenitic, AISI 303, free-machining	0.83
Stainless steel, austenitic, AISI 304	0.72
Tool steel	0.51
Bronze and brass:	
Soft	1.7- 2.5
Medium	1.0 - 1.4
Hard	0.6 - 1.0
Aluminum and magnesium	2.5 - 4.0
Monel metal	0.55
Copper, annealed	0.84
Nickel	0.53
Titanium & alloys	0.75 - 1.1

NOTE: "K" values are in cubic inches per minute per cutter horsepower (in^3/min/hp_c)

Figure 7.68 *K*-factor table.

Suggested Feed per Tooth for Milling - High-Speed Steel Cutters (Tabulated Data in Inches)

Material	Face mills	Helical mills	Slot/side mills	End mills	Form-relieved cutters
Magnesium & alloys	0.022	0.018	0.013	0.011	0.007
Aluminum & Alloys	0.022	0.018	0.013	0.011	0.007
Free-cutting brasses & bronzes	0.022	0.018	0.013	0.011	0.007
Medium brasses & bronzes	0.014	0.011	0.008	0.007	0.004
Hard brasses & bronzes	0.009	0.007	0.006	0.005	0.003
Copper	0.012	0.010	0.007	0.006	0.004
Cast iron, soft (150-180 Bhn)	0.016	0.013	0.009	0.008	0.005
Cast iron, medium (180-220 Bhn)	0.013	0.010	0.007	0.007	0.004
Cast iron, hard (220-300 Bhn)	0.011	0.008	0.006	0.006	0.003
Malleable iron	0.012	0.010	0.007	0.006	0.004
Cast steel	0.012	0.010	0.007	0.006	0.004
Low-carbon steel, free-machining	0.012	0.010	0.007	0.006	0.004
Low-carbon steels	0.010	0.008	0.006	0.005	0.003
Medium-carbon steels	0.010	0.008	0.006	0.005	0.003
Alloy steel, ann'ld (180-220 Bhn)	0.008	0.007	0.005	0.004	0.003
Alloy steel, tough (220-300 Bhn)	0.006	0.005	0.004	0.003	0.002
Alloy steel, hard (300-400 Bhn)	0.004	0.003	0.003	0.002	0.002
Stainless steels, free-machining	0.010	0.008	0.006	0.005	0.003
Stainless steels	0.006	0.005	0.004	0.003	0.002
Monel metal	0.008	0.007	0.005	0.004	0.003
Titanium & alloys	0.008	0.007	0.005	0.004	0.003
Machinable plastics	0.013	0.010	0.008	0.007	0.004

NOTE: Tabular data in inches. For feed per tooth in millimeters, multiply tabular data by 25.4. For carbon-steel cutter multiply tabular data by 0.50 or divide by 2. Source: Cincinnati Milicron, Inc.

Figure 7.69 Milling feed table, HSS.

$$\text{rpm} = \frac{S}{(D/12)\pi} \quad \text{or} \quad \frac{S}{0.26D}$$

When it is necessary to increase the production rate, it is better to change the cutter material rather than to increase the cutting speed. Increasing the cutting speed alone may shorten the life of the cutter because the cutter is usually being operated at its maximum speed for optimal productivity.

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General rules for selection of the cutting speed

- Use lower cutting speeds for longer tool life.
- Take into account the Brinell hardness of the material.
- Use the lower range of recommended cutting speeds when starting a job.
- For a fine finish, use a lower feed rate in preference to a higher cutting speed.

Number of cutter teeth. The number of cutter teeth N required for a particular application may be found from the simple expression (not applicable to carbide or other high-speed cutters)

$$N = \frac{f}{F_t C_{\text{rpm}}}$$

where f = feed rate, ipm
F_t = feed per tooth (chip thickness), in
C_{rpm} = rotational speed of cutter, rpms
N = number of cutter teeth

An industry-recommended equation for calculating the number of cutter teeth required for a particular operation is

$$N = 19.5\sqrt{R} - 5.8$$

where N = number of cutter teeth
R = radius of cutter, in

This simple equation is suitable for HSS cutters only and is not valid for carbide, cobalt cast alloy, or other high-speed cutting tool materials.

Figure 7.70 gives recommended cutting speed ranges (sfpm) for HSS cutters. See the figures in feeds and speeds section for carbide, cermet, ceramic, and other high-speed advanced cutting materials.

Milling horsepower. Ratios for metal removal per horsepower (cubic inches per minute per horsepower at the milling cutter) have been given for various materials (see Fig. 7.68). The general equation is

$$K = \frac{\text{in}^3/\text{min}}{\text{hp}_c} = \frac{WHf}{\text{hp}_c}$$

where K = metal removal factor, $\text{in}^3/\text{min}/\text{hp}_c$ (see Fig. 7.68)
hp_c = horsepower at the cutter

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Milling Cutting Speeds for Various Materials
(sfpm) Surface feet per minute (High-speed steel tools only)

Material	High-speed steel tools Rough	Finish
Cast iron	50 - 60	80 - 110
Semisteel	40 - 50	65 - 90
Malleable iron	80 - 100	110 - 130
Cast steel	45 - 60	70 - 90
Copper	100 - 150	150 - 200
Brass	200 - 300	200 - 300
Bronze	100 - 150	150 - 180
Aluminum	400 - 450	700 - 750
* Magnesium	600 - 800	1,000 - 1,500
SAE steels:		
1020 (coarse feed), low-carbon	60 - 80	60 - 80
1020 (fine feed), low-carbon	100 - 120	100 - 120
1035, medium-carbon	75 - 90	90 - 120
1330, alloy steel	90 - 110	90 - 110
1050, Med-high-carbon	60 - 80	100 - 125
2315, nickel steel	90 - 110	90 - 110
3150, nickel-chromium	50 - 60	70 - 90
4150, chrome-molybdenum	40 - 50	70 - 90
4340, nickel-chrome-molybdenum	40 - 50	60 - 70
Stainless steel	60 - 80	100 - 120
Titanium, hard alloy	80 - 100	110 - 130

NOTE: Tabular data ranges are in sfpm (surface feet per minute for HSS cutters only).
* A fire hazard is present when machining magnesium at high-speeds.

Figure 7.70 Milling cutting speeds, HSS.

W = width of cut, in
H = depth of cut, in
f = feed rate, ipm

The total horsepower required at the cutter may then be expressed as

$$\text{hp}_c = \frac{\text{in}^3/\text{min}}{K} \qquad \text{or} \qquad \frac{WHf}{K}$$

The K factor varies with type and hardness of material and for the same material varies with the feed per tooth, increasing as the chip thickness increases. The K factor represents a particular rate of metal removal and not a general or average rate. For a quick approximation of total power requirements at the machine motor, see Fig. 7.71, which gives the maximum metal-removal rates for different horsepower-rated milling machines cutting different materials.

7.2.2 Feeds and speeds for milling with advanced cutting tool materials

Figures 7.14 through 7.44 present the feeds and speeds with which materials may be milled using the carbide, cermet, ceramic, and advanced cutting tool materials such as cubic boron nitride (CBN)

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Milling-Machine Horsepower Ratings - for maximum metal removal rates (in^3/min) for HSS (high-speed steel cutters)

Workpiece Material	Rated hp of Machine									
	3	5	7.5	10	15	20	25	30	40	50
	Max. Metal Removal (in^3/min)									
Aluminum	2.7	5.5	8.7	12	18	27	37	48	69	91
Brass, soft	2.4	4.7	7.5	10	16	24	32	41	60	79
Bronze, hard	1.7	3.3	5.3	7.3	11	17	23	30	43	56
Bronze, very hard	0.78	1.6	2.5	3.4	5.3	7.8	11	15	20	26
Cast iron, soft	1.6	3.2	5.2	7.1	11	16	22	28	41	54
Cast iron, hard	1	2	3.3	4.6	7	10	14	18	26	35
Cast iron, chilled	0.78	1.6	2.5	3.4	5.3	7.8	10	13	19	26
Malleable iron	1	2.1	3.4	4.7	7.3	11	14	18	26	36
Steel, soft	1	2	3.3	4.6	7	10	14	18	26	35
Steel, medium	0.78	1.6	2.5	3.4	5.3	7.8	10	13	19	26
Steel, hard	0.56	1.1	1.8	2.5	3.9	5.7	7.7	10	14	19

NOTE: Data source - Kearney & Trecker Corp.

Figure 7.71 Milling machine horsepower ratings.

that are used widely in industry today. Cutting tool technology has advanced rapidly, and new tools and materials are being made available at a rapid pace. Nevertheless, the data presented here are the latest available at the date of publication of this *Handbook*.

Modern theory of milling. The key characteristics of the milling process are

- Simultaneous motion of cutter rotation and feed movement of the workpiece
- Interrupted cut
- Production of tapered chips

It was common practice for many years in the industry to mill against the direction of feed. This was due to the type of tool materials then available (HSS) and the absence of antibacklash devices on the machines. This method became known as "conventional" or "up milling" and is illustrated in Fig. 7.72*b*. "Climb milling" or "down milling" is now the preferred method of milling with advanced cutting tool materials such as carbides, cermets, CBN, etc. Climb milling is illustrated in Fig. 7.72*a*. Here, the insert enters the cut with some chip load and proceeds to produce a chip that thins as it progresses toward the end of the cut. This allows the heat generated in the cutting process to dissipate into the chip. Climb-milling forces push the workpiece toward the clamping fixture, in the direction of the feed. Conventional-milling (up-milling)

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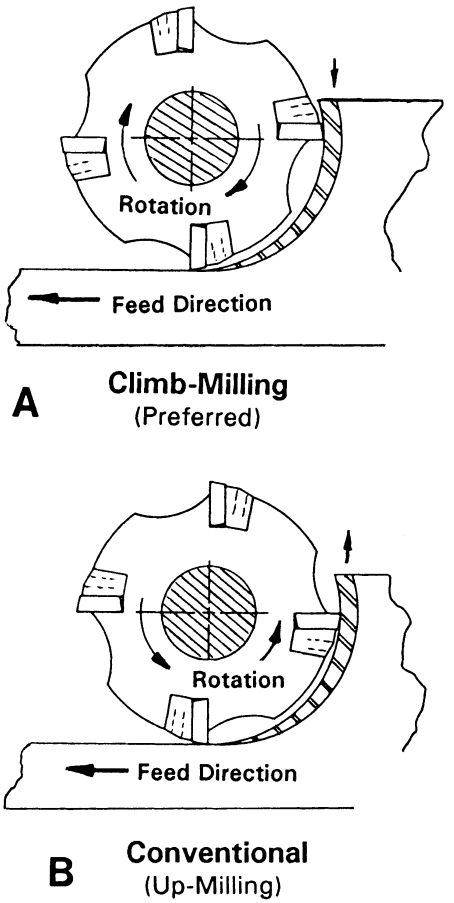

Figure 7.72 Climb and up milling.

forces are against the direction of feed and produce a lifting force on the workpiece and clamping fixture.

The angle of entry is determined by the position of the cutter centerline in relation to the edge of the workpiece. A negative angle of entry β is preferred and is illustrated in Fig. 7.73*b*, where the centerline of the cutter is below the edge of the workpiece. A negative angle is preferred because it ensures contact with the workpiece at the strongest point of the insert cutter. A positive angle of entry

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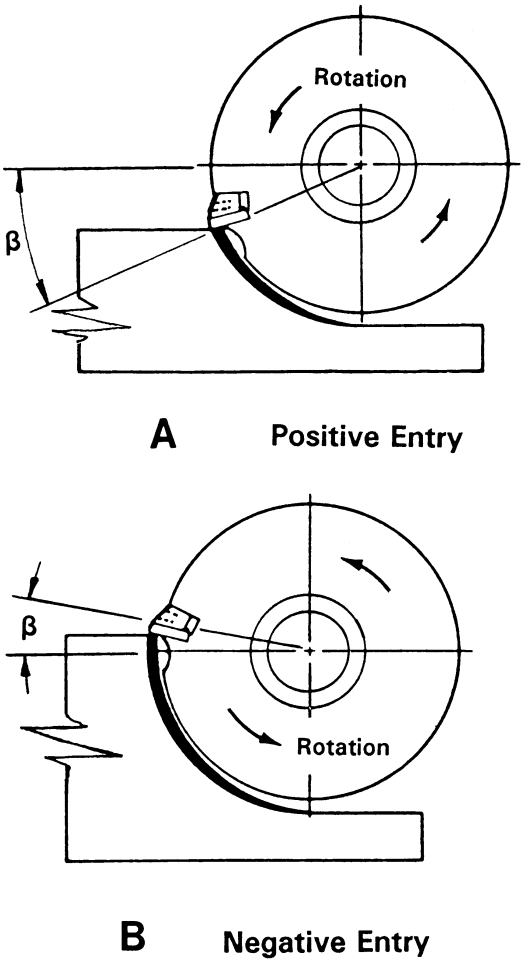

Figure 7.73 Milling entry angles.

will increase insert chipping. If a positive angle of entry must be employed, use an insert with a honed or negative land.

Figure 7.74*a* shows an eight-tooth cutter climb milling a workpiece using a negative angle of entry, and the feed, or advance, per revolution is 0.048 in with a chip load per tooth of 0.006 in. The following milling formulas will allow you to calculate the various milling parameters.

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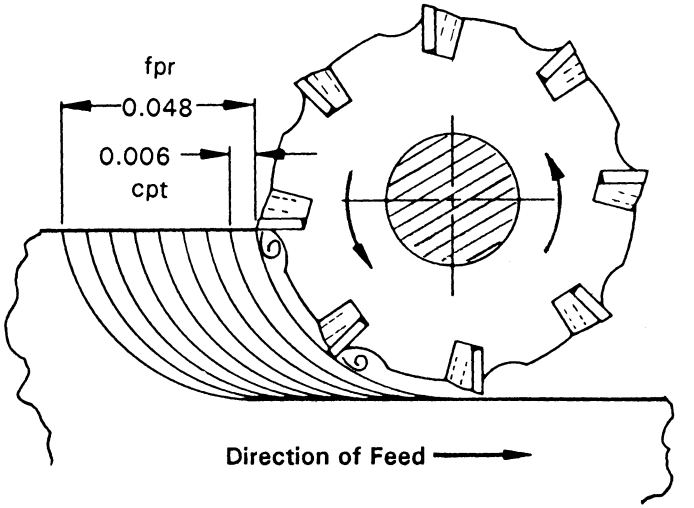

(a)

Power Constant Factor (P_f) for Milling Various Materials

P_f = cubic inches of metal removal per single horsepower

Material	P_f Factor
Free-machining aluminum alloys	0.20
Gray cast irons	0.25
Non-ferrous free-machining alloys	0.45
Alloy cast irons and ductile irons	0.50
Martensitic stainless steels	0.81
Titanium	0.87
Free-machining carbon steel	0.89
Standard carbon steel	0.92
Alloy steels	0.95
Austenitic stainless steel	0.96
High-temperature alloys	1.00
Tool steels	1.05
Cobalt based alloys	1.20

Note: The P_f factors will vary per feed rate (ipm) and Brinell hardness (Bhn).
The P_f factors in the table are for normal feed rates and material hardness ranges to 285 Bhn.
A 15 hp spindle-rated mill should be able to machine 15 x 0.92 = 13.8 cubic inches of standard plain carbon steel per minute.

(b)

Figure 7.74 (*a*) Milling principle. (*b*) Power constants for milling.

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In the following formulas,

n_t = number of teeth or inserts in the cutter

cpt = chip load per tooth or insert, in

ipm = feed, inches per minute

fpr = feed (advance) per revolution, in

D = cutter effective cutting diameter, in

rpm = revolutions per minute

sfpm = surface feet per minute (also termed sfm)

$$\text{sfpm} = \frac{\pi D(\text{rpm})}{12} \qquad \text{rpm} = \frac{12(\text{sfpm})}{\pi D} \qquad \text{fpr} = \frac{\text{ipm}}{\text{rpm}}$$

$$\text{ipm} = \text{cpt} \times n_t \times \text{rpm} \qquad \text{cpt} = \frac{\text{ipm}}{n_t(\text{rpm})} \qquad \text{or} \qquad \frac{\text{fpr}}{n_t}$$

Example: Given a cutter of 5 in diameter, eight teeth, 500 sfpm, and 0.007 cpt,

$$\text{rpm} = \frac{12 \times 500}{3.1415 \times 5} = 382$$

$$\text{ipm} = 0.007 \times 8 \times 382 = 21.4$$

$$\text{fpr} = \frac{21.4}{382} = 0.056$$

Slotting. Special consideration is given for slot milling, and the following equations may be used effectively to calculate chip load per tooth (cpt) and inches per minute (ipm):

$$\text{cpt} = \frac{\left(\dfrac{\sqrt{(D-x)x}}{r}\right)\left(\dfrac{\text{ipm}}{\text{rpm}}\right)}{\text{number of effective teeth}}$$

$$\text{ipm} = \text{rpm} \times \text{number of effective teeth} \left[\frac{\text{cpt}}{\dfrac{\sqrt{(D-x)x}}{r}}\right]$$

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where D = diameter of slot cutter, in
r = radius of cutter, in
x = depth of slot, in
cpt = chip load per tooth, in
ipm = feed, inches per minute
rpm = rotational speed of cutter, rpm

Milling horsepower for advanced cutting tool materials

Horsepower consumption. It is advantageous to calculate the milling operational horsepower requirements before starting a job. Lower-horsepower machining centers take advantage of the ability of the modern cutting tools to cut at extremely high surface speeds (sfpm). Knowing your machine's speed and feed limits could be critical to your obtaining the desired productivity goals. The condition of your milling machine is also critical to obtaining these productivity goals. Older machines with low-spindle-speed capability should use the uncoated grades of carbide cutters and inserts.

Horsepower calculation. A popular equation used in industry for calculating horsepower at the spindle is

$$\text{hp} = \frac{M_{rr} P_f}{E_s}$$

where M_{rr} = metal removal rate, in^3/min
P_f = power constant factor (see Fig. 7.74*b*)
E_s = spindle efficiency, 0.80 to 0.90 (80 to 90 percent)

Note: The spindle efficiency is a reflection of losses from the machine's motor to actual power delivered at the cutter and must be taken into account, as the equation shows.

A table of P_f factors is shown in Fig. 7.74*b* and represents the number of cubic inches of material that may be removed per each (1) horsepower input at the spindle or cutter for different types of materials.

Note: The metal removal rate M_{rr} = depth of cut × width of cut × ipm = in^3/min.

Axial cutting forces at various lead angles. Axial cutting forces vary as you change the lead angle of the cutting insert. The 0° lead angle produces the minimum axial force into the part. This is advantageous for weak fixtures and thin web sections. The 45° lead angle loads the spindle with the maximum axial force, which is advantageous when using the older machines.

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Tangential cutting forces. The use of a tangential-force equation is appropriate for finding the approximate forces that fixtures, part walls, or webs and the spindle bearings are subjected to during the milling operation. The tangential force is calculated easily when you have determined the horsepower being used at the spindle or cutter. It is important to remember that the tangential forces decrease as the spindle speed (rpms) increases, i.e., at higher surface feet per minute. The ability of the newer advanced cutting tools to operate at higher speeds thus produces fewer fixture- and web-deflecting forces with a decrease in horsepower requirements for any particular machine. Some of the new high-speed cutter inserts can operate efficiently at speeds of 10,000 sfpm or higher when machining such materials as free-machining aluminum and magnesium alloys.

The tangential force developed during the milling operations may be calculated from

$$t_f = \frac{126{,}000\text{hp}}{\pi D(\text{rpm})}$$

where t_f = tangential force, pounds force
hp = horsepower at the spindle or cutter
D = effective diameter of cutter, in
rpm = rotational speed in revolutions per minute

The preceding calculation procedure for finding the tangential forces developed on the workpiece being cut may be used in conjunction with the clamping fixture types and clamping calculations shown in Chap. 8, "Tooling Practices."

7.2.3 Feeds and speeds tables: Advanced cutting tools and inserts

See Sec. 7.1.8 and Figs. 7.14 through 7.44.

How to apply the range of conditions for the preceding feeds and speeds tables is shown in Fig. 7.75. A chart of carbide insert-grade comparisons for different manufacturers is shown in Fig. 7.76. Insert-grade comparisons may be made using this chart, although the chart is a guide only and indicates those grades having similar properties under most conditions. It is not intended to imply that all cross-referenced grades are exact duplicates in physical and metallurgical characteristics or that they perform equally in the same applications. Figure 7.76 is used for older inserts. See Figs. 7.45 and 7.46 for newer inserts.

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-GENERAL APPLICATIONS FOR CUTTING CONDITIONS-		
CONDITION	-SPEED-	-FEED-
Roughing	⇩	⇧
Finishing	⇧	⇩
End Milling	⇧	⇩
Slotting	⇧	⇩
Hard Material	⇩	⇨
Soft Material	⇧	⇧
Scale	⇩	⇧
Tool Life	⇩	⇨
Heavy d.o.c.	⇩	⇩

Higher- ⇧

Lower- ⇩

Same- ⇨

Figure 7.75 Applying range of conditions—milling tables.

Cutter speed (rpm) from surface speed (sfpm). A time-saving table of surface speed versus cutter speed is shown in Fig. 7.77 for cutter diameters from 0.25 through 5 in. For cutter speed (rpm) values when the surface speed is greater than 200 sfpm, use the simple equation

$$\text{rpm} = \frac{12(\text{sfpm})}{\pi D}$$

where D is the effective diameter of cutter in inches.

7.2.4 Milling accessories

Many types of accessories are available for various milling capabilities, and a few basic ones are shown here. Figure 7.78 shows the

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(Obosolete Carbide Grade Comparison)

Kenna-metal	IMCO	Adamas	Carboloy	Carmet	New-comber	Sandvic	SECO	Firth Sterling	TRW	Valenite	VR/ Wesson	Walmet
Uncoated Grades												
K1	IC-10	B	44A	CA-3	N-10			H-6	CQ-12	VC-1	VR-54	WA-1
K68	MG-10	PWX	820	CA-310		H10	G-27	H-17	CQ-22	VC-27	RAM-1	WA-10
K68	IC-20	A	883	CA-4	N-22	H20	H-13	H-21	CQ-2	VC-2	2A5	WA-2
K313	IC-40	AAA	999	CA-8	N-40	H05		HF	CQ-4	VC-4		WA-4
K420	IC-50	434	390	CA-740	N-50		S6	T-04	CY-12		2A7	WA-54
K420	IC-55	499	370	CA-720	N-55	S6	S6	T-12	CY-16	VC-5	VR-75	WA-5
K2884	IC-67	548		CA-717	N-60	SIP	S2	T-25	CY-14	VC-6	VR-73	WA-47
K313	IC-70	490	350		N-70	SIP	SIG	T-25	CY-31	VC-8		WA-73
Coated Grades												
KC730	IC-202	ACT-2	523	CA9443	NT-2	GC315	TP-15	TC	027	VN2	630	P2
KC810	IC-552	ACT-5	550	CA9720	NT-5	GC1025	TP-35	HN	715	VN5	660	P5
KC850	IC-672	ACT-7	518		NT-8		TP-25	TC1	714		670	P47
KC910	IC-554	ROXIDE	570		NA02	GC015		CC46	918	V01		A60
KC950	IC-674		545			GC415		CC44		V05	680	A62

NOTE: This grade selection chart is intended to be used as a guide to grade selection of various manufacturers. It indicates those grades having similar characteristics under most general conditions. It is not intended to imply that all comparable grades are exact duplicates in physical and metallurgical properties, or that they perform exactly the same on all applications.

Figure 7.76 Carbide insert-grade comparison for various manufacturers.

CUTTER SPEEDS IN REVOLUTIONS PER MINUTE

Diameter of cutter (in.)	Surface speed (ft. per min.)															
	25	30	35	40	50	55	60	70	75	80	90	100	120	140	160	180	200
	Cutter revolutions per minute																
1/4	382	458	535	611	764	851	917	1,070	1,147	1,222	1,376	1,528	1,834	2,139	2,445	2,750	3,056
5/16	306	367	428	489	611	672	733	856	917	978	1,100	1,222	1,466	1,711	1,955	2,200	2,444
3/8	255	306	357	408	509	560	611	713	764	815	916	1,018	1,222	1,425	1,629	1,832	2,036
7/16	218	262	306	349	437	481	524	611	656	699	786	874	1,049	1,224	1,398	1,573	1,748
1/2	191	229	268	306	382	420	459	535	573	611	688	764	917	1,070	1,222	1,375	1,528
5/8	153	184	214	245	306	337	367	428	459	489	552	612	736	857	979	1,102	1,224
3/4	127	153	178	203	254	279	306	357	381	408	458	508	610	711	813	914	1,016
7/8	109	131	153	175	219	241	262	306	329	349	392	438	526	613	701	788	876
1	95.5	115	134	153	191	210	229	267	287	306	344	382	458	535	611	688	764
1-1/4	76.3	91.8	107	123	153	168	183	214	230	245	274	306	367	428	490	551	612
1-1/2	63.7	76.3	89.2	102	127	140	153	178	191	204	230	254	305	356	406	457	508
1-3/4	54.5	65.5	76.4	87.3	109	120	131	153	164	175	196	218	262	305	349	392	436
2	47.8	57.3	66.9	76.4	95.5	105	115	134	143	153	172	191	229	267	306	344	382
2-1/2	38.2	45.8	53.5	61.2	76.3	84.2	91.7	107	114	122	138	153	184	213	245	275	306
3	31.8	38.2	44.6	51	63.7	69.9	76.4	89.1	95.3	102	114	127	152	178	208	228	254
3-1/2	27.3	32.7	38.2	44.6	54.5	60	65.5	76.4	81.8	87.4	98.1	109	131	153	174	196	218
4	23.9	28.7	33.4	38.2	47.8	52.6	57.3	66.9	71.7	76.4	86	95.6	115	134	153	172	191
5	19.1	22.9	26.7	30.6	38.2	42	45.9	53.5	57.3	61.1	68.8	76.4	91.7	107	122	138	153

Figure 7.77 Cutter revolutions per minute from surface speed.

widely used horizontal dividing and angle-setting tool. With this accessory, you may divide the circle into an equal number of divisions or set any horizontal angle from a particular baseline or starting point. The vernier on this device will set an angle within ±15 minutes of arc. The clamping table or surface of this device can be rotated a full 360°. Figure 7.79 shows a vertical dividing head for milling operations.

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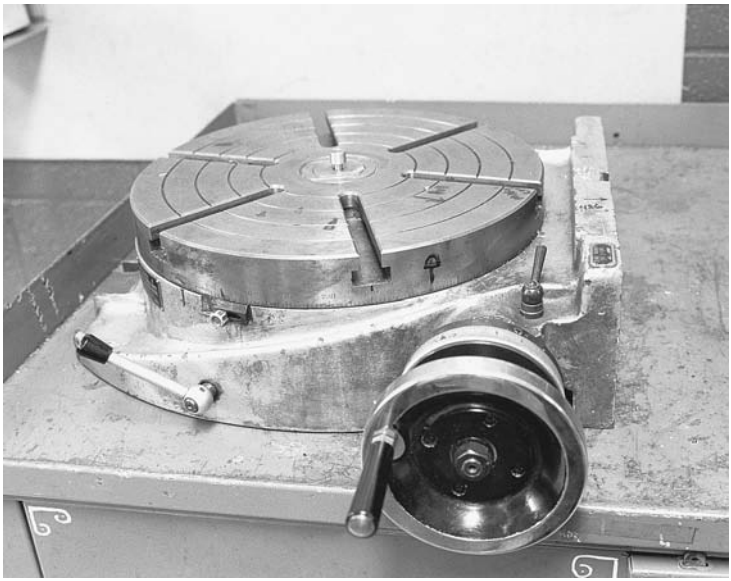

Figure 7.78 Horizontal dividing and angle-setting head.

Figure 7.79 Vertical dividing head for milling operations.

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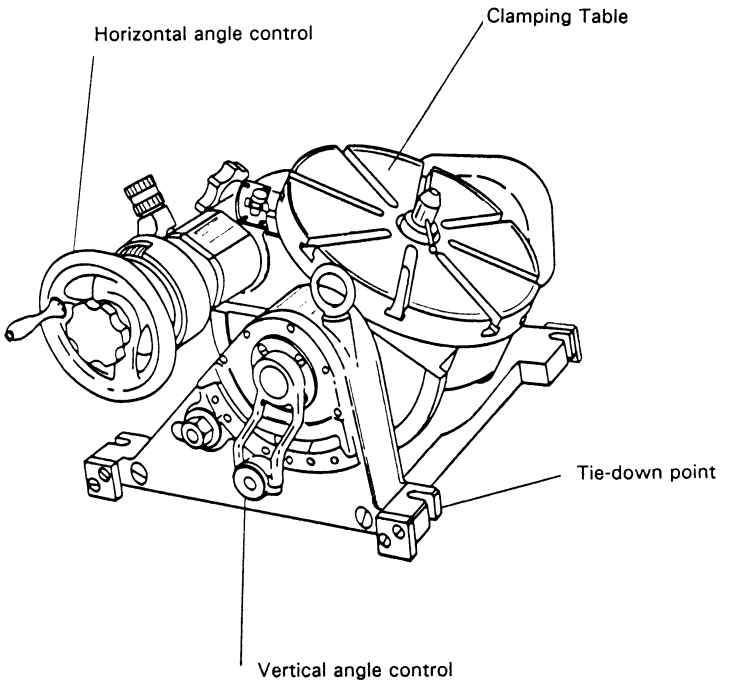

Figure 7.80 Vertical and horizontal angle-setting device.

The device shown in Fig. 7.80 will allow the setting of a compound angle because the clamping table on this device can be rotated both horizontally and vertically, and both directions are controlled by a vernier setting. This device is similar to a compound sine plate but is perhaps more convenient and easier to use, although the compound sine plate is more accurate owing to the fact that it is set using Jo-blocks. Previous chapters of this *Handbook* explain the use and setting practices of compound sine plates and simple sine plates.

Quick answers to milling calculations can be obtained by using the various cutting tool manufacturers' calculators. With these devices, all the basic milling calculations can be done, including the required horsepower needed for a particular milling operation. When a device such as this is not available to the tool or manufacturing engineer or machinist, the calculations may be performed by using the equations and charts presented in this section. This device is similar to the turning and boring calculator shown in the turning

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and boring section (Sec. 7.1), except that it has been designed for use in milling operations.

Standard dividing and indexing head procedures are shown in Sec. 7.12.8.

Machining calculations. Although the modern machining centers can set angles and compound angles through the programmed controller on these machines, the basic accessories are nonetheless important when used on manually set machines, such as those used for small production runs and in prototype and model shops. Many of the machining procedures and calculations would indeed be complex without the use of the modern machining center equipped for four- or five-axis operations.

It should be apparent that the basic milling machine and machining center also can be used for drilling and jig-boring operations, although on a limited scale in relation to the available horsepower and physical size of the machine. Figure 7.81 illustrates some of the basic cutting tools used on mills and machining centers. In the figure, parts *a*, *b*, and *c* are drill bits that have been coated with titanium nitride, part *d* is a typical ball-end mill, part *e* is a high-speed close-spiral tap, whereas parts *f*, *g*, and *h* are a

Figure 7.81 Titanium nitride–coated drills and end mills.

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newer type end-mill design used for roughing operations at high speed, where large volumes of material are removed very rapidly. In parts *f*, *g*, and *h*, notice the threadlike grooves in the spiral flutes, which allow a rapid roughing operation to be performed. A close examination of the photograph will reveal the line on the tools that shows where the titanium nitride coating ends. The titanium nitride coating imparts a gold-colored finish on these cutting tools that is not apparent in the black and white photograph.

7.3 Drills and Drilling

Drilling is a machining operation for producing round holes in metallic and nonmetallic materials. A drill is a rotary-end cutting tool with one or more cutting edges or lips and one or more straight or helical grooves or flutes for the passage of chips and cutting fluids and coolants. When the depth of a drilled hole reaches three or four times the drill diameter, a reduction must be made in the drilling feed and speed. A coolant-hole drill can produce drilled depths to eight or more times the diameter of the drill. The gun drill can produce an accurate hole to depths of more than 100 times the diameter of the drill with great precision.

Enlarging a drilled hole for a portion of its depth is called *countersinking*, whereas a counterbore for cleaning the surface a small amount around the hole is called *spotfacing*. Cutting an angular bevel at the perimeter of a drilled hole is also termed *countersinking*. Countersinking tools are available to produce 82°, 90°, and 100° countersinks and other special angles.

Drills are classified by material, length, shape, number, type of helix or flute, shank, point characteristics, and size series. Most drills are made for right-hand rotation. Right-hand drills, as viewed from their point, with the shank facing away from your view, are rotated in a counterclockwise direction in order to cut. Left-hand drills cut when rotated clockwise in a similar manner.

7.3.1 Drill terminology

Figure 7.81*a* to *c* shows common twist drills made of HSS steel and coated with titanium nitride. The line just above the flutes shows the limit of the titanium nitride coating. Figure 7.82 shows the standard twist-drill form with the appropriate terminology describing its characteristic features.

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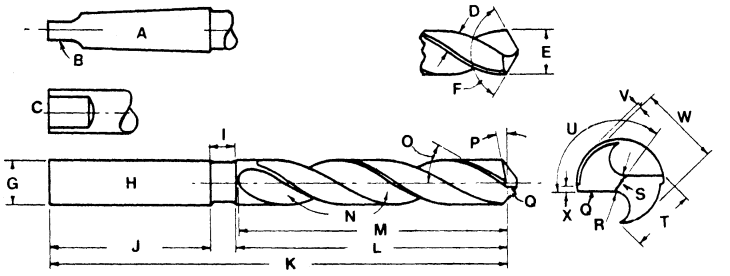

Twist Drill Features

A	Taper shank	M	Flute length
B	Tang	N	Flutes
C	Tang drive	O	Helix angle
D	Land width	P	Lip relief angle
E	Drill diameter	Q	Lip
F	Point angle	R	Web
G	Shank diameter	S	Chisel edge
H	Straight shank	T	Land
I	Neck	U	Chisel edge angle
J	Shank length	V	Body diameter clearance
K	Overall length	W	Clearance diameter
L	Body	X	Margin

Figure 7.82 Twist-drill features.

Drill types or styles

- HSS jobber drills
- Solid-carbide jobber drills
- Carbide-tipped screw-machine drills
- HSS screw-machine drills
- Carbide-tipped glass drills
- HSS extralong straight-shank drills (24 in)
- Taper-shank drills (0 through number 7 ANSI taper)
- Core drills
- Coolant-hole drills
- HSS taper-shank extralong drills (24 in)
- Aircraft extension drills (6 and 12 in)
- Gun drills

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- HSS half-round jobber drills
- Spotting and centering drills
- Parabolic drills
- S-point drills
- Square solid-carbide die drills
- Spade drills
- Miniature drills
- Microdrills and microtools

American national standard tapers. Figure 7.83 shows the American national standard taper geometry and dimensions for ANSI tapers 1 through 7. Taper number 0 is not listed in the national standards. Table 7.1 accompanies Fig. 7.83 and lists the detail dimensions.

7.3.2 Drill point styles and angles

Over a period of many years, the metalworking industry has developed many different drill point styles for a wide variety of applications from drilling soft plastics to drilling the hardest types of metal alloys. All the standard point styles and special points are shown in Fig. 7.84, including the important point angles that differentiate these different points. New drill styles are being introduced

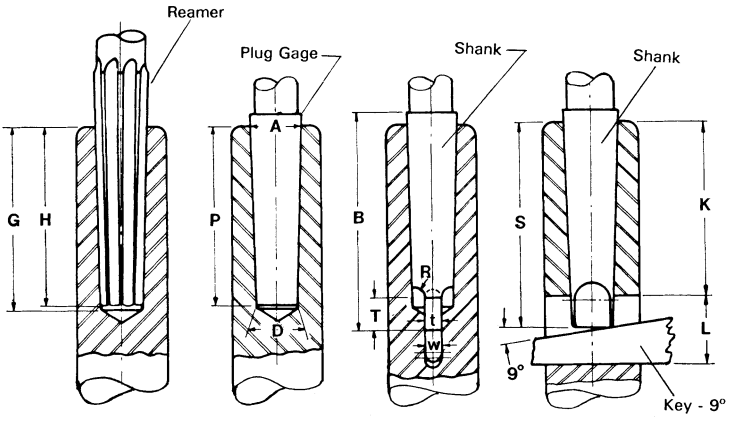

Figure 7.83 American national standard tapers.

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TABLE 7.1 Detail Dimensions* for American National Standard Tapers

	Shank								Tang				Tang Slot					
American national standard taper number	Diam. of plug at small end	Diam. at end of socket	Whole length	Depth	Depth of drilled hole	Depth of reamed hole	Standard plug depth		Thickness	Length	Radius	Radius	Width	Length	End of socket to tang slot	Taper per inch	Taper per foot	American national standard taper number
	D	*A*	*B*	*S*	*G*	*H*	*P*		*t*	*T*	*R*	*a*	*W*	*L*	*K*			
0†	0.25200	0.35610	2 11/32	2 7/32	2 1/16	2 1/32	2		5/32	1/4	5/32	3/64	11/64	9/16	1 15/16	0.052050	0.62460	0†
1	0.36900	0.47500	2 9/16	2 7/16	2 3/16	2 5/32	2 1/8		13/64	3/8	3/16	3/64	7/32	3/4	2 1/16	0.049882	0.59858	1
2	0.57200	0.70000	3 1/8	2 15/16	2 21/32	2 39/64	2 9/16		1/4	7/16	1/4	1/16	17/64	7/8	2 1/2	0.049951	0.59941	2
3	0.77800	0.93800	3 7/8	3 11/16	3 5/16	3 1/4	3 3/16		5/16	9/16	9/32	5/64	21/64	1 3/16	3 1/16	0.050196	0.60235	3
4	1.02000	1.23100	4 7/8	4 5/8	4 3/16	4 1/8	4 1/16		15/32	5/8	5/16	3/32	31/64	1 1/4	3 7/8	0.051938	0.62326	4
4 1/2	1.26600	1.50000	5 3/8	5 1/8	4 5/8	4 9/16	4 1/2		9/16	11/16	3/8	1/8	37/64	1 3/8	4 5/16	0.052000	0.62400	4 1/2
5	1.47500	1.74800	6 1/8	5 7/8	5 5/16	5 1/4	5 3/16		5/8	3/4	3/8	1/8	21/32	1 1/2	4 15/16	0.052626	0.63151	5
6	2.11600	2.49400	8 9/16	8 1/4	7 13/32	7 21/64	7 1/4		3/4	1 1/8	1/2	5/32	25/32	1 3/4	7	0.052138	0.62565	6
7	2.75000	3.27000	11 5/8	11 1/4	10 5/32	10 5/64	10		1 1/8	1 3/8	3/4	3/16	1 5/32	2 5/8	9 1/2	0.052000	0.62400	7

* Table agrees with American national standards for taper shanks except for angle and undercut of tang.
† Size 0 taper shank not listed in American national standards.

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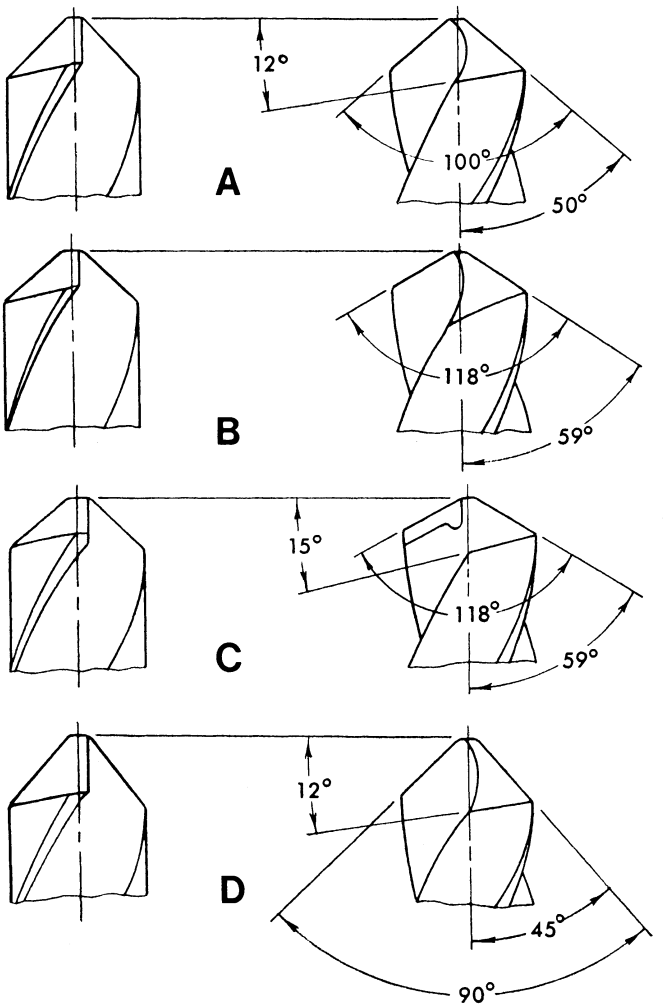

Figure 7.84 Drill-point styles and angles.

periodically, but the styles shown in Fig. 7.84 include some of the newer types, as well as the commonly used older configurations.

The old practice of grinding drill points by hand and eye is, at the least, ineffective with today's modern drills and materials. For a drill to perform accurately and efficiently, modern drill-grinding

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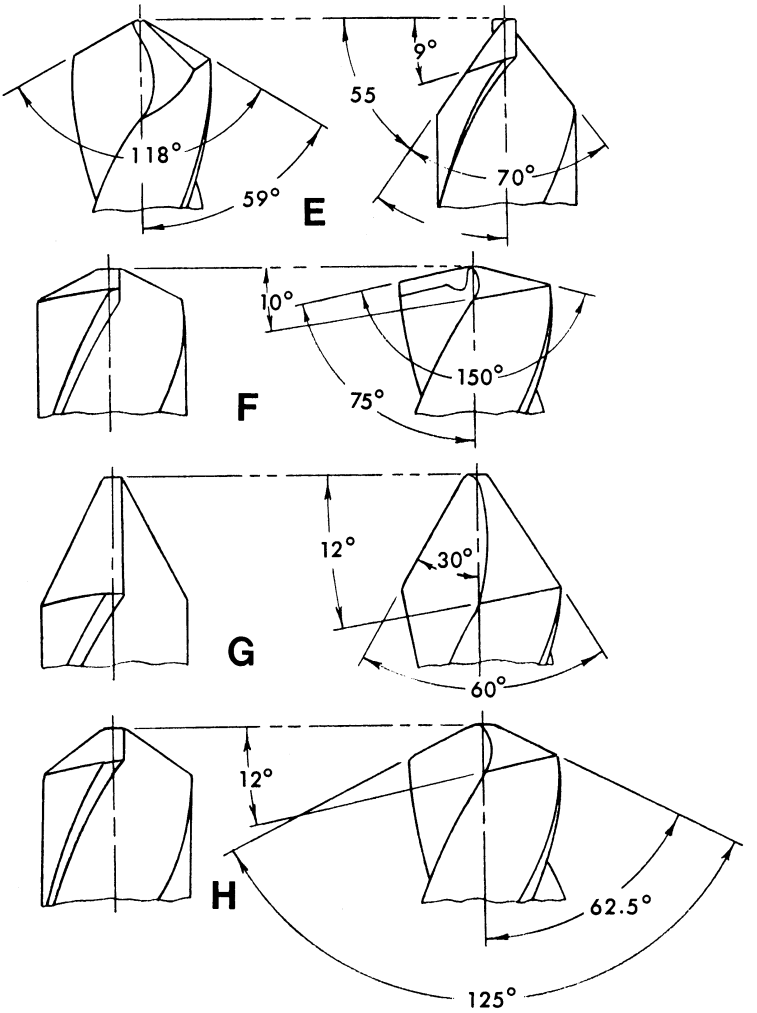

Figure 7.84 (*Continued*)

machines such as the models produced by the Darex Corporation are required. Models are also produced that are capable of sharpening taps, reamers, end mills, and countersinks. Metalcutting tool sharpening and grinding practices are not detailed in this *Handbook*. The tool suppliers and tool-sharpening vendors are equipped

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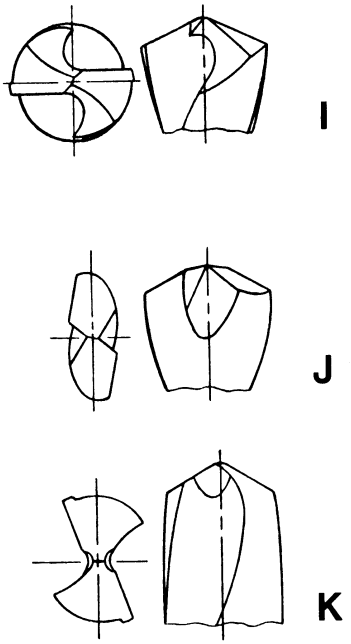

Figure 7.84 (*Continued*)

to sharpen all the cutting tools they distribute in a more accurate and efficient manner than can be done by hand in modern machine shops. HSS- and cobalt-based turning bits are an exception to this modern grinding and sharpening practice, in that the machinist or machine operator occasionally dresses or hones such a cutting tool.

Recommended general uses for drill point angles shown in Fig. 7.84 are shown below. Figure 7.84*k* illustrates web thinning of a standard twist drill.

Typical uses

A	Copper and medium to soft copper alloys
B	Molded plastics, Bakelite, etc.
C	Brasses and soft bronzes
D	Alternate for G, cast irons, die castings, and aluminum
E	Crankshafts and deep holes
F	Manganese steel and hard alloys (point angle 125° to 135°)

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G Wood, fiber, hard rubber, and aluminum

H Heat-treated steels and drop forgings

I Split point, 118° or 135° point, self-centering (CNC applications)

J Parabolic flute for accurate, deep holes and rapid cutting

K Web thinning (thin the web as the drill wears from resharpening; this restores the chisel point to its proper length)

Other drill styles that are used today include the helical or S-point, which is self-centering and permits higher feed rates, and the chamfered point, which is effective in reducing burr generation in many materials.

Drills are produced from HSS and solid carbide or with carbide-brazed inserts. Drill systems are made by many of the leading tool manufacturers that allow the use of removable inserts of carbide, cermet, ceramics, and cubic boron nitride (CBN). Many of the HSS twist drills used today have coatings such as titanium nitride, titanium carbide, aluminum oxide, and other tremendously hard and wear-resistant coatings. These coatings can increase drill life by as much as three to five times over premium HHS and plain carbide drills.

7.3.3 Classification of high-speed steels

Figure 7.85 shows the chemical composition and characteristics of the M and T series of HSSs. The classification shown applies to drills, turning tools, mills, and other tools made of HSS and is of great value in selecting the proper type of HSS tool for the intended application in machining.

7.3.4 Conversion of surface speed to revolutions per minute for drills

Fractional drill sizes. Figure 7.86 shows the standard fractional drill sizes and the revolutions per minute of each fractional drill size for various surface speeds. The drilling-speed tables that follow give the allowable drilling speed (sfpm) of the various materials. From these values, the correct rpm setting for drilling can be ascertained using the speed/rpm tables given here.

Wire drill sizes (1 through 80). See Fig. 7.87*a* and *b*.

Letter drill sizes. See Fig. 7.88.

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CLASSIFICATION of HIGH-SPEED STEELS

Chemical Composition						Comparative Physical Properties *			
AISI - SAE Grade	Tungsten	Chromium	Vanadium	Molybdenum	Cobalt	Red Hardness	Abrasion Resistance	Edge Strength	Grinding Ability
M - 1	1.5	4.0	1.0	8.5	-	10	10	18	18
M - 2	6.0	4.0	2.0	5.0	-	10	11	17	17
M - 3-1	6.0	4.0	2.4	6.0	-	10	14	12	8
M - 3-2	6.0	4.0	3.0	6.0	-	10	17	11	6
M - 4	5.5	4.5	4.0	4.5	-	10	18	8	5
M - 7	1.7	4.0	2.0	8.75	-	10	12	17	14
M - 10	-	4.0	2.0	8.0	-	10	10	17	17
M - 15	6.5	4.5	5.0	3.0	5.0	13	19	9	2
M - 30	2.0	4.0	1.0	8.0	5.0	13	10	14	14
M - 34	2.0	4.0	2.0	8.5	8.0	15	11	14	14
M - 36	6.0	4.0	2.0	6.0	9.0	16	11	14	14
M - 42	1.5	3.75	1.15	9.5	8.0	17	19	15	14
T - 1	18.0	4.0	1.0	-	-	10	10	16	18
T - 2	18.0	4.0	2.0	-	-	10	11	15	17
T - 3	18.0	4.0	3.0	-	-	10	14	8	7
T - 4	18.0	4.0	1.0	-	5.0	13	10	11	14
T - 5	18.0	4.0	2.0	-	8.0	15	11	11	14
T - 6	22.0	4.5	1.5	-	12.0	20	10	11	14
T - 15	13.0	4.5	5.0	-	5.0	17	20	9	2

* Comparative Range of Physical Properties:
0 - 4 = Poor; 5 - 8 = Fair; 9 - 12 = Good; 13 - 16 = Very Good; 17 - 20 = Excellent

Figure 7.85 Classification of HSSs.

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FRACTIONAL SIZE DRILLS

Surface Feet per Minute

Diam. Inches	10'	12'	15'	20'	25'	30'	35'	40'	45'	50'	60'	70'	80'	90'	100'
	Revolutions per Minute														
1/64	2445	2934	3667	4889	6112	7334	8556	9778	11001	12223	14668	17112	19557	22001	24446
1/32	1222	1467	1833	2445	3056	3667	4278	4889	5500	6112	7334	8556	9778	11001	12223
3/64	815	978	1222	1630	2037	2445	2852	3259	3667	4074	4889	5704	6519	7334	8149
1/16	611	733	917	1222	1528	1833	2139	2445	2750	3056	3667	4278	4889	5500	6112
5/64	489	587	733	978	1222	1467	1711	1956	2200	2445	2934	3422	3911	4400	4889
3/32	407	489	611	815	1019	1222	1426	1630	1833	2037	2445	2852	3259	3667	4074
7/64	349	419	524	698	873	1048	1222	1397	1572	1746	2095	2445	2794	3143	3492
1/8	306	367	458	611	764	917	1070	1222	1375	1528	1833	2139	2445	2750	3056
9/64	272	326	407	543	679	815	951	1086	1222	1358	1630	1901	2173	2445	2716
5/32	244	293	367	489	611	733	856	978	1100	1222	1467	1711	1956	2200	2445
11/64	222	267	333	444	556	667	778	889	1000	1111	1333	1556	1778	2000	2222
3/16	204	244	306	407	509	611	713	815	917	1019	1222	1426	1630	1833	2037
13/64	188	226	282	376	470	564	658	752	846	940	1128	1316	1504	1692	1880
7/32	175	210	262	349	437	524	611	698	786	873	1048	1222	1397	1572	1746
15/64	163	196	244	326	407	489	570	652	733	815	978	1141	1304	1467	1630
1/4	153	183	229	306	382	458	535	611	688	764	917	1070	1222	1375	1528
9/32	136	163	204	272	340	407	475	543	611	679	815	951	1086	1222	1358
5/16	122	147	183	244	306	367	428	489	550	611	733	856	978	1100	1222
11/32	111	133	167	222	278	333	389	444	500	556	667	778	889	1000	1111
3/8	102	122	153	204	255	306	357	407	458	509	611	713	815	917	1019
13/32	94	113	141	188	235	282	329	376	423	470	564	658	752	846	940
7/16	87	105	131	175	218	262	306	349	393	437	524	611	698	786	873
15/32	81	98	122	163	204	244	285	326	367	407	489	570	652	733	815
1/2	76	92	115	153	191	229	267	306	344	382	458	535	611	688	764
9/16	68	81	102	136	170	204	238	272	306	340	407	475	543	611	679
5/8	61	73	92	122	153	183	214	244	275	306	367	428	489	550	611
11/16	56	67	83	111	139	167	194	222	250	278	333	389	444	500	556
3/4	51	61	76	102	127	153	178	204	229	255	306	357	407	458	509
13/16	47	56	71	94	118	141	165	188	212	235	282	329	376	423	470
7/8	44	52	65	87	109	131	153	175	196	218	262	306	349	393	437
15/16	41	49	61	81	102	122	143	163	183	204	244	285	326	367	407
1	38	46	57	76	95	115	134	153	172	191	229	267	306	344	382
1-1/8	34	41	51	68	85	102	119	136	153	170	204	238	272	306	340
1-1/4	31	37	46	61	76	92	107	122	138	153	183	214	244	275	306
1-3/8	28	33	42	56	69	83	97	111	125	139	167	194	222	250	278
1-1/2	25	31	38	51	64	76	89	102	115	127	153	178	204	229	255
1-5/8	24	28	35	47	59	71	82	94	106	118	141	165	188	212	235
1-3/4	22	26	33	44	55	65	76	87	98	109	131	153	175	196	218
1-7/8	20	24	31	41	51	61	71	81	92	102	122	143	163	183	204
2	19	23	29	38	48	57	67	76	86	95	115	134	153	172	191
2-1/4	17	20	25	34	42	51	59	68	76	85	102	119	136	153	170
2-1/2	15	18	23	31	38	46	53	61	69	76	92	107	122	138	153
2-3/4	14	17	21	28	35	42	49	56	63	69	83	97	111	125	139
3	13	15	19	25	32	38	45	51	57	64	76	89	102	115	127
3-1/2	11	13	16	22	27	33	38	44	49	55	65	76	87	98	109

For speeds higher than tabulated, multiply all values by 10 or 100. For speeds lower than tabulated, divide all values by 10.

Figure 7.86 Drill rpm/surface speed, fractional drills.

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WIRE SIZE DRILLS

Surface Feet per Minute

	10'	12'	15'	20'	25'	30'	35'	40'	45'	50'	60'	70'	80'	90'	100'
Diam. No.	Revolutions per Minute														
1	168	201	251	335	419	503	586	670	754	838	1005	1173	1340	1508	1675
2	173	207	259	346	432	519	605	691	778	864	1037	1210	1382	1555	1728
3	179	215	269	359	448	538	628	717	807	897	1076	1255	1434	1614	1793
4	183	219	274	366	457	548	640	731	822	914	1097	1280	1462	1645	1828
5	186	223	279	372	465	558	651	743	836	930	1115	1301	1487	1673	1859
6	187	225	281	374	468	562	655	749	843	936	1123	1310	1498	1685	1872
7	190	228	285	380	475	570	665	760	855	950	1140	1330	1520	1710	1900
8	192	230	288	384	480	576	672	768	864	960	1151	1343	1535	1727	1919
9	195	234	292	390	487	585	682	780	877	975	1169	1364	1559	1754	1949
10	197	237	296	395	494	592	691	790	888	987	1184	1382	1579	1777	1974
11	200	240	300	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
12	202	243	303	404	505	606	707	808	909	1010	1213	1415	1617	1819	2021
13	206	248	310	413	516	619	723	826	929	1032	1239	1450	1652	1859	2065
14	210	252	315	420	525	630	735	839	944	1050	1259	1469	1679	1889	2099
15	212	255	318	424	531	637	743	849	955	1064	1276	1489	1702	1914	2127
16	216	259	324	432	540	647	755	863	971	1079	1295	1511	1726	1942	2158
17	221	265	331	442	552	662	773	883	994	1104	1325	1546	1766	1987	2208
18	225	270	338	451	563	676	789	901	1014	1130	1356	1582	1808	2034	2260
19	230	276	345	460	575	690	805	920	1035	1151	1381	1611	1841	2071	2301
20	237	285	356	474	593	712	830	949	1068	1186	1423	1660	1898	2135	2372
21	240	288	360	480	601	721	841	961	1081	1201	1441	1681	1922	2162	2402
22	243	292	365	487	608	730	852	973	1095	1217	1460	1703	1946	2190	2433
23	248	298	372	496	620	744	868	992	1116	1240	1488	1736	1984	2232	2480
24	251	302	377	503	628	754	880	1005	1131	1257	1508	1759	2010	2262	2513
25	255	307	383	511	639	766	894	1022	1150	1276	1533	1789	2044	2300	2555
26	260	312	390	520	650	780	909	1039	1169	1299	1559	1819	2078	2338	2598
27	265	318	398	531	663	796	928	1061	1194	1327	1592	1857	2122	2388	2653
28	272	326	408	544	680	816	952	1087	1223	1360	1631	1903	2175	2447	2719
29	281	337	421	562	702	843	983	1123	1264	1405	1685	1966	2247	2528	2809
30	297	357	446	595	743	892	1040	1189	1338	1487	1784	2081	2378	2676	2973
31	318	382	477	637	796	955	1114	1273	1432	1592	1910	2228	2546	2865	3183
32	329	395	494	659	823	988	1152	1317	1482	1647	1976	2305	2634	2964	3293
33	338	406	507	676	845	1014	1183	1352	1521	1690	2028	2366	2704	3042	3380
34	344	413	516	688	860	1032	1204	1376	1549	1721	2065	2409	2753	3097	3442
35	347	417	521	694	868	1042	1215	1389	1563	1736	2083	2430	2778	3125	3472
36	359	430	538	717	897	1076	1255	1435	1614	1794	2152	2511	2870	3228	3587
37	367	441	551	735	918	1102	1285	1469	1653	1837	2204	2571	2938	3306	3673
38	376	452	564	753	941	1129	1317	1505	1693	1882	2258	2634	3010	3387	3763
39	384	461	576	768	960	1152	1344	1536	1728	1920	2303	2687	3071	3455	3839
40	390	468	585	780	974	1169	1364	1559	1754	1949	2339	2729	3118	3508	3898

For speeds higher than tabulated, multiply all values by 10 or 100. For speeds lower than tabulated, divide all values by 10.

Figure 7.87 Drill rpm/surface speed, wire-size drills.

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WIRE SIZE DRILLS

Surface Feet per Minute

Diam. No.	10'	12'	15'	20'	25'	30'	35'	40'	45'	50'	60'	70'	80'	90'	100'
	Revolutions per Minute														
41	398	477	597	796	995	1194	1393	1592	1790	1990	2387	2785	3183	3581	3979
42	409	490	613	817	1021	1226	1430	1634	1838	2043	2451	2860	3268	3677	4085
43	429	515	644	858	1073	1288	1502	1717	1931	2146	2575	3004	3434	3863	4292
44	444	533	666	888	1110	1332	1555	1777	1999	2221	2665	3109	3554	3999	4442
45	466	559	699	932	1165	1397	1630	1863	2096	2329	2795	3261	3726	4192	4658
46	472	566	707	943	1179	1415	1650	1886	2122	2358	2830	3301	3773	4244	4716
47	487	584	730	973	1216	1460	1703	1946	2190	2433	2920	3406	3893	4379	4866
48	503	603	754	1005	1256	1508	1759	2010	2262	2513	3016	3518	4021	4523	5026
49	523	628	785	1046	1308	1570	1831	2093	2355	2617	3140	3663	4186	4710	5233
50	546	655	819	1091	1364	1637	1910	2183	2456	2729	3274	3820	4366	4911	5457
51	570	684	855	1140	1425	1710	1995	2280	2565	2851	3421	3991	4561	5131	5701
52	602	722	902	1203	1504	1805	2105	2406	2707	3008	3609	4211	4812	5414	6015
53	642	770	963	1284	1605	1926	2247	2568	2889	3207	3848	4490	5131	5773	6414
54	694	833	1042	1389	1736	2083	2431	2778	3125	3473	4167	4862	5556	6251	6945
55	735	881	1102	1469	1836	2204	2571	2938	3306	3673	4408	5142	5877	6611	7346
56	821	986	1232	1643	2054	2464	2875	3286	3696	4108	4929	5751	6572	7394	8215
57	888	1066	1332	1777	2221	2665	3109	3553	3997	4452	5342	6232	7122	8013	8903
58	909	1091	1364	1819	2274	2728	3183	3638	4093	4547	5456	6367	7275	8186	9095
59	932	1118	1397	1863	2329	2795	3261	3726	4192	4658	5590	6521	7453	8388	9316
60	955	1146	1432	1910	2387	2865	3342	3820	4297	4775	5729	6684	7639	8594	9549
61	979	1175	1469	1959	2449	2938	3428	3918	4407	4897	5876	6856	7835	8815	9794
62	1005	1206	1508	2010	2513	3016	3518	4021	4523	5025	6030	7035	8040	9045	10050
63	1032	1239	1549	2065	2581	3097	3613	4129	4646	5160	6192	7224	8256	9288	10320
64	1061	1273	1592	2122	2653	3183	3714	4244	4775	5305	6366	7427	8488	9549	10610
65	1091	1310	1637	2183	2728	3274	3820	4365	4911	5455	6546	7637	8728	9819	10910
66	1157	1389	1736	2315	2894	3472	4051	4630	5207	5790	6948	8106	9264	10422	11580
67	1194	1432	1790	2387	2984	3581	4178	4775	5371	5970	7164	8358	9552	10746	11940
68	1232	1479	1848	2464	3080	3696	4313	4929	5545	6160	7392	8624	9856	11088	12320
69	1308	1570	1962	2616	3270	3924	4578	5232	5887	6530	7836	9142	10488	11754	13060
70	1364	1637	2046	2728	3410	4093	4775	5457	6139	6820	8184	9548	10912	12276	13640
71	1469	1763	2204	2938	3673	4407	5142	5876	6611	7365	8838	10311	11784	13257	14730
72	1528	1833	2272	3056	3820	4584	5348	6112	6875	7640	9168	10696	12224	13752	15280
73	1592	1910	2387	3183	3979	4775	5570	6366	7162	7960	9552	11144	12736	14328	15920
74	1698	2037	2546	3395	4244	5093	5942	6791	7639	8510	10212	11914	13616	15318	17020
75	1819	2183	2728	3638	4547	5457	6366	7276	8185	9095	10914	12733	14552	16371	18190
76	1910	2292	2865	3820	4775	5730	6684	7639	8594	9550	11460	13370	15280	17190	19100
77	2122	2546	3183	4244	5305	6366	7427	8488	9549	10610	12732	14854	16976	19098	21220
78	2387	2865	3581	4775	5968	7162	8356	9549	10743	11935	14322	16709	19096	21483	23870
79	2634	3161	3951	5269	6586	7903	9220	10537	11854	13170	15804	18438	21072	23706	26340
80	2829	3395	4244	5659	7074	8488	9903	11318	12732	14150	16980	19810	22640	25470	28300

For speeds higher than tabulated, multiply all values by 10 or 100. For speeds lower than tabulated, divide all values by 10.

Figure 7.87 (*Continued*)

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LETTER SIZE DRILLS

Surface Feet per Minute

Letter Size	10'	12'	15'	20'	25'	30'	35'	40'	45'	50'	60'	70'	80'	90'	100'
	Revolutions per Minute														
A	163	196	245	326	408	490	571	653	735	818	982	1145	1309	1472	1636
B	160	193	241	321	401	481	562	642	722	803	963	1124	1284	1445	1605
C	158	189	237	316	395	473	552	631	710	789	947	1105	1262	1420	1578
D	155	186	233	311	388	466	543	621	699	778	934	1089	1245	1400	1556
E	153	183	229	306	382	458	535	611	687	764	917	1070	1222	1375	1528
F	149	178	223	297	372	446	520	595	669	743	892	1040	1189	1337	1486
G	146	176	220	293	366	439	512	585	659	732	878	1024	1170	1317	1463
H	144	172	215	287	359	431	503	574	646	718	862	1005	1149	1294	1436
I	140	169	211	281	351	421	492	562	632	702	842	983	1123	1264	1404
J	138	165	207	276	345	414	483	552	621	690	827	965	1103	1241	1379
K	136	163	204	272	340	408	476	544	612	680	815	951	1087	1223	1359
L	132	158	198	263	329	395	461	527	593	659	790	922	1054	1185	1317
M	129	155	194	259	324	388	453	518	583	648	777	907	1036	1166	1295
N	126	152	190	253	316	379	442	506	569	633	759	886	1012	1139	1265
O	121	145	181	242	302	363	423	484	544	605	725	846	967	1088	1209
P	118	142	177	237	296	355	414	473	532	592	710	828	946	1065	1183
Q	115	138	173	230	288	345	403	460	518	575	690	805	920	1035	1150
R	113	135	169	225	282	338	394	451	507	564	676	789	902	1014	1127
S	110	132	165	220	274	329	384	439	494	549	659	769	878	988	1098
T	107	128	160	213	267	320	373	427	480	533	640	746	853	959	1066
U	104	125	156	208	259	311	363	415	467	519	623	727	830	934	1038
V	101	122	152	203	253	304	355	405	456	507	608	709	810	912	1013
W	99	119	148	198	247	297	346	496	445	495	594	693	792	891	989
X	96	115	144	192	240	289	337	385	433	481	576	672	769	865	962
Y	95	113	142	189	236	284	331	378	425	473	567	662	756	851	945
Z	92	111	139	185	231	277	324	370	416	462	555	647	740	832	925

For speeds higher than tabulated, multiply all values by 10 or 100. For speeds lower than tabulated divide all values by 10.

Figure 7.88 Drill rpm/surface speed, letter-size drills.

7.3.5 Tap drill sizes for producing unified inch screw threads, metric and pipe threads

Tap drills for unified inch screw threads. See Fig. 7.89.

Tap-drill sizes for producing metric screw threads. See Fig. 7.90.

Tap-drill sizes for pipe threads (taper and straight pipe). See Fig. 7.91.

Equation for obtaining tap-drill sizes for cutting taps

$$D_h = D_{bm} - 0.0130\left(\frac{\%\text{ of full size thread desired}}{n_i}\right)$$ for unified inch-size threads

$$D_{h1} = D_{bm1} - \left(\frac{\%\text{ of full size thread desired}}{76.98}\right)$$ for metric series threads

where D_h = drilled hole size, in

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D_{h1} = drilled hole size, mm
D_{bm} = basic major diameter of thread, in
D_{bm1} = basic major diameter of thread, mm
n_i = number of threads per inch

Note: In the preceding equations, use the percentage whole number; i.e., for 84 percent, use 84.

Example: What is the drilled hole size in inches for a ⅜-16 tapped thread with 84 percent of full thread?

$$D_h = 0.375 - 0.0130 \times \left(\frac{84}{16}\right) = 0.30675 \text{ in}$$

0.30675 in is then the decimal equivalent of the required tap drill for 84 percent of full thread. Use the next-closest drill size, which would be letter size N (0.302 in). The diameters of the American standard wire and letter-size drills are shown in Fig. 7.92. For metric tapped holes, see Fig. 7.93.

When producing a tapped hole, be sure that the correct class of fit is satisfied, i.e., class 2B, 3B, interference fit, etc. The different classes of fits for the thread systems are shown in the section on ANSI and American Society of Mechanical Engineers (ASME) standards; see Chap. 17 on ANSI standards applicable to machining and metalworking. Certain fit classes allow for electroplating and other characteristics that are determined by the design engineer, who selects the class of fit for a particular application.

7.3.6 Speeds and feeds, drill geometry,and cutting recommendations for drills

The composite drilling table shown in Fig. 7.94 has been derived from data originated by the Society of Manufacturing Engineers (SME) and various major drill manufacturers. Figure 7.95 illustrates the standard drill point and split point together with the chisel-edge angle range in common use.

7.3.7 Spade drills

Spade drills are used to produce holes ranging from 1 to over 6 in in diameter. Very deep holes can be produced with spade drills,

(Text continued on page 465.)

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Tap size	Tap drill size	Decimal equiv. of tap drill, in	Theoretical percent of thread, %	Probable mean over-size, in	Probable hole size, in	Probable percent of thread,* %
0–80	56	0.0465	83	0.0015	0.0480	74
	3/64	0.0469	81	0.0015	0.0484	71
	1.20 mm	0.0472	79	0.0015	0.0487	69
	1.25 mm	0.0492	67	0.0015	0.0507	57
1–64	54	0.0550	89	0.0015	0.0565	81
	1.45 mm	0.0571	78	0.0015	0.0586	71
	53	0.0595	67	0.0015	0.0610	59
1–72	1.5 mm	0.0591	77	0.0015	0.0606	68
	53	0.0595	75	0.0015	0.0610	67
	1.55 mm	0610	67	0.0015	0.0606	68
2–56	51	0.0670	82	0.0017	0.0687	74
	1.75 mm	0.0689	73	0.0017	0.0706	66
	50	0.0700	69	0.0017	0.0717	62
	1.80 mm	0.0709	65	0.0017	0.0726	58
2–64	50	0.0700	79	0.0017	0.0717	70
	1.80 mm	0.0709	74	0.0017	0.0726	66
	49	0.0730	64	0.0017	0.0747	56
3–48	48	0.0760	85	0.0019	0.0779	78
	5/64	0.0781	77	0.0019	0.0800	70
	47	0.0785	76	0.0019	0.0804	69
	2.00 mm	0.0787	75	0.0019	0.0806	68
	46	0.0810	67	0.0019	0.0829	60
	45	0.0820	63	0.0019	0.0839	56
3–56	46	0.0810	78	0.0019	0.0829	69
	45	0.0820	73	0.0019	0.0839	65
	2.10 mm	0.0827	70	0.0019	0.0846	62
	2.15 mm	0.0846	62	0.0019	0.0865	54
4–40	44	0.0860	80	0.0020	0.0880	74
	2.20 mm	0.0866	78	0.0020	0.0886	72
	43	0.0890	71	0.0020	0.0910	65
	2.30 mm	0.0906	66	0.0020	0.0926	60
4–48	2.35 mm	0.0925	72	0.0020	0.0926	72
	42	0.0935	68	0.0020	0.0955	61
	3/32	0.0938	68	0.0020	0.0958	60
	2.40 mm	0.0945	65	0.0020	0.0965	57
5–40	40	0.0980	83	0.0023	0.1003	76
	39	0.0995	79	0.0023	0.1018	71
	38	0.1015	72	0.0023	0.1038	65
	2.60 mm	0.1024	70	0.0023	0.1047	63

Figure 7.89 Tap-drill sizes, unified inch screw threads.

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Tap size	Tap drill size	Decimal equiv. of tap drill, in	Theoretical percent of thread, %	Probable mean over-size, in	Probable hole size, in	Probable percent of thread,* %
5–44	38	0.1015	79	0.0023	0.1038	72
	2.60 mm	0.1024	77	0.0023	0.1047	69
	37	0.1040	71	0.0023	0.1063	63
6–32	37	0.1040	84	0.0023	0.1063	78
	36	0.1065	78	0.0023	0.1088	72
	7/64	0.1095	70	0.0026	0.1120	64
	35	0.1100	69	0.0026	0.1126	63
	34	0.1100	67	0.0026	0.1136	60
6–40	34	0.1110	83	0.0026	0.1136	75
	33	0.1130	77	0.0026	0.1156	69
	2.90 mm	0.1142	73	0.0026	0.1168	65
	32	0.1160	68	0.0026	0.1186	60
8–32	3.40 mm	0.1339	74	0.0029	0.1368	67
	29	0.1360	69	0.0029	0.1389	62
8–36	29	0.1360	78	0.0029	0.1389	70
	3.5 mm	0.1378	72	0.0029	0.1407	65
10–24	27	0.1440	85	0.0032	0.1472	79
	3.70 mm	0.1457	82	0.0032	0.1489	76
	26	0.1470	79	0.0032	0.1502	74
	25	0.1495	75	0.0032	0.1527	69
	24	0.1520	70	0.0032	0.1552	64
10–32	5/32	0.1563	83	0.0032	0.1595	75
	22	0.1570	81	0.0032	0.1602	73
	21	0.1590	76	0.0032	0.1622	68
12–24	11/64	0.1719	82	0.0035	0.1754	75
	17	0.1730	79	0.0035	0.1765	73
	16	0.1770	72	0.0035	0.1805	66
12–28	16	0.1770	84	0.0035	0.1805	77
	15	0.1800	78	0.0035	0.1835	70
	4.60 mm	0.1811	75	0.0035	0.1846	67
	14	0.1820	73	0.0035	0.1855	66
1/4–20	9	0.1960	83	0.0038	0.1998	77
	8	0.1990	79	0.0038	0.2028	73
	7	0.2010	75	0.0038	0.2048	70
	13/64	0.2031	72	0.0038	0.2069	66
1/4–28	5.40 mm	0.2126	81	0.0038	0.2164	72
	3	0.2130	80	0.0038	0.2168	72
5/16–18	F	0.2570	77	0.0038	0.2608	72
	6.60 mm	0.2598	73	0.0038	0.2636	68
	G	0.2610	71	0.0041	0.2651	66
5/16–24	H	0.2660	86	0.0041	0.2701	78
	6.80 mm	0.2677	83	0.0041	0.2718	75

Figure 7.89 (*Continued*)

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Tap size	Tap drill size	Decimal equiv. of tap drill, in	Theoretical percent of thread, %	Probable mean over-size, in	Probable hole size, in	Probable percent of thread,* %
	I	0.2720	75	0.0041	0.2761	67
3/8–16	7.80 mm	0.3071	84	0.0044	0.3115	78
	7.90 mm	0.3110	79	0.0044	0.3154	73
	5/16	0.3125	77	0.0044	0.3169	72
	O	0.3160	73	0.0044	0.3204	68
8–24	21/64	0.3281	87	0.0044	0.3325	79
	8.40 mm	0.3307	82	0.0044	0.3351	74
	Q	0.3320	79	0.0044	0.3364	71
	8.50 mm	0.3346	75	0.0044	0.3390	67
7/16–14	T	0.3580	86	0.0046	0.3626	81
	23/64	0.3594	84	0.0046	0.3640	79
	9.20 mm	0.3622	81	0.0046	0.3668	76
	9.30 mm	0.3661	77	0.0046	0.3707	72
	U	0.3680	75	0.0046	0.3726	70
	9.40 mm	0.3701	73	0.0046	0.3747	68
7/16–20	W	0.3860	79	0.0046	0.3906	72
	25/64	0.3906	72	0.0046	0.3952	65
1/2–13	10.50 mm	0.4134	87	0.0047	0.4181	82
	27/64	0.4219	78	0.0047	0.4266	73
1/2–20	29/64	0.4531	72	0.0047	0.4578	65
9/16–12	15/32	0.4688	87	0.0048	0.4736	82
	31/64	0.4844	72	0.0048	0.4892	68
9/16–18	1/2	0.5000	87	0.0048	0.5048	80
5/8–11	17/32	0.5313	79	0.0049	0.5362	75
5/8–18	9/16	0.5625	87	0.0049	0.5674	80
3/4–10	41/64	0.6406	84	0.0050	0.6456	80
	21/32	0.6563	72	0.0050	0.6613	68
1/4–16	11/16	0.6875	77	0.0050	0.6925	71
	17.50 mm	0.6890	75	0.0050	0.6940	69
7/8–9	49/64	0.7656	76	0.0052	0.7708	72
7/8–14	51/64	0.7969	84	0.0052	0.8021	79
1–8	55/64	0.8594	87	0.0059	0.8653	83
	7/8	0.8750	77	0.0059	0.8809	73
1–12	29/32	0.9063	87	0.0059	0.9122	81
	59/64	0.9219	72	0.0060	0.9279	67
1–14	59/64	0.9219	84	0.0060	0.9279	78
1 1/8–7	31/32	0.9688	84	0.0062	0.9750	81
	63/64	0.9844	76	0.0067	0.9911	72
1 1/8–12	1 1/32	1.0313	87	0.0071	1.0384	80

Figure 7.89 (*Continued*)

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Machining, Machine Tools, and Practices

Metric Tap size	Tap drill size	Decimal equiv. of tap drill, in	Theoretical percent of thread, %	Probable mean over-size, in	Probable hole size, in	Probable percent of thread,* %
M1.6 × 0.35	1.20 mm	0.0472	88	0.0014	0.0486	80
	1.25 mm	0.0492	77	0.0014	0.0506	69
M2 × 0.4	1/16	0.0625	79	0.0015	0.0640	72
	1.60 mm	0.0630	77	0.0017	0.0647	69
	52	0.0635	74	0.0017	0.0652	66
M2.5 × 0.45	2.05 mm	0.0807	77	0.0019	0.0826	69
	46	0.0810	76	0.0019	0.0829	67
	45	0.0820	71	0.0019	0.0839	63
M3 × 0.5	40	0.0980	79	0.0023	0.1003	70
	2.5 mm	0.0984	77	0.0023	0.1007	68
	39	0.0995	73	0.0023	0.1018	64
M3.5 × 0.6	33	0.1130	81	0.0026	0.1156	72
	2.9 mm	0.1142	77	0.0026	0.1163	68
	32	0.1160	71	0.0026	0.1186	63
M4 × 0.7	3.2 mm	0.1260	88	0.0029	0.1289	80
	30	0.1285	81	0.0029	0.1314	73
	3.3 mm	0.1299	77	0.0029	0.1328	69
M4.5 × 0.75	3.7 mm	0.1457	82	0.0032	0.1489	74
	26	0.1470	79	0.0032	0.1502	70
	25	0.1495	72	0.0032	0.1527	64
M5 × 0.8	4.2 mm	0.1654	77	0.0032	0.1686	69
	19	0.1660	75	0.0032	0.1692	68
M6 × 1	10	0.1935	84	0.0038	0.1973	76
	9	0.1960	79	0.0038	0.1998	71
	5 mm	0.1968	77	0.0038	0.2006	70
	8	0.1990	73	0.0038	0.2028	65
M7 × 1	A	0.2340	81	0.0038	0.2378	74
	6 mm	0.2362	77	0.0038	0.2400	70
	B	0.2380	74	0.0038	0.2418	66
M8 × 1.25	6.7 mm	0.2638	80	0.0041	0.2679	74
	17/64	0.2656	77	0.0041	0.2697	71
	H	0.2660	77	0.0041	0.2701	70
	6.8 mm	0.2677	74	0.0041	0.2718	68
M10 × 1.5	8.4 mm	0.3307	82	0.0044	0.3351	76
	Q	0.3320	80	0.0044	0.3364	75
	8.5 mm	0.3346	77	0.0044	0.3390	71
M12 × 1.75	10.25 mm	0.4035	77	0.0047	0.4082	72
	Y	0.4040	76	0.0047	0.4087	71
	13/32	0.4062	74	0.0047	0.4109	69
M14 × 2	15/32	0.4688	81	0.0048	0.4736	76
	12 mm	0.4724	77	0.0048	0.4772	72

Figure 7.90 Tap-drill sizes, metric screw threads.

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Metric Tap size	Tap drill size	Decimal equiv. of tap drill, in	Theoretical percent of thread, %	Probable mean over-size, in	Probable hole size, in	Probable percent of thread,* %
M16 × 2	35/64	0.5469	81	0.0049	0.5518	76
	14 mm	0.5512	77	0.0049	0.5561	72
M20 × 2.5	11/16	0.6875	78	0.0050	0.6925	74
	17.5 mm	0.6890	77	0.0052	0.6942	73
M24 × 3	13/16	0.8125	86	0.0052	0.8177	82
	21 mm	0.8268	76	0.0054	0.8322	73
	53/64	0.8281	76	0.0054	0.8335	73
M30 × 3.5	1 1/32	1.0312	83	0.0071	1.0383	80
	25.1 mm	1.0394	79	0.0071	1.0465	75
	1 3/64	1.0469	75	0.0072	1.0541	70
M36 × 4	1 17/64	1.2656	74	Reaming recommended		

Figure 7.90 (*Continued*)

Taper pipe		Straight pipe	
Thread	Drill	Thread	Drill
1/8–27	R	1/8–27	S
1/4–18	7/16	1/4–18	29/64
3/8–18	37/64	3/8–18	19/32
1/2–14	23/32	1/2–14	47/64
3/4–14	59/64	3/4–14	15/16
1–11½	1 5/32	1–11½	1 3/16
1¼–11½	1½	1¼–11½	1 33/64
1½–1½	1 47/64	1½–11½	1¾
2–11½	2 7/32	2–11½	2 7/32
2½–8	2⅝	2½–8	2 21/32
3–8	3¼	3–8	3 9/32
3½–8	3¾	3½–8	3 25/32
4–8	4¼	4–8	4 9/32

Figure 7.91 Pipe taps.

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Machining, Machine Tools, and Practices

DRILL NO.	DECIMAL	DRILL NO.	DECIMAL	DRILL NO.	DECIMAL
97	0.0059	56	0.0465	15	0.180
96	0.0063	55	0.052	14	0.182
95	0.0067	54	0.055	13	0.185
94	0.0071	53	0.0595	12	0.189
93	0.0075	52	0.0635	11	0.191
92	0.0079	51	0.067	10	0.1935
91	0.0083	50	0.070	9	0.196
90	0.0087	49	0.073	8	0.199
89	0.0091	48	0.076	7	0.201
88	0.0095	47	0.0785	6	0.204
87	0.010	46	0.076	5	0.2055
86	0.0105	45	0.082	4	0.209
85	0.011	44	0.086	3	0.213
84	0.0115	43	0.089	2	0.221
83	0.012	42	0.0935	1	0.228
82	0.0125	41	0.096	A	0.234
81	0.013	40	0.098	B	0.238
80	0.0135	39	0.0995	C	0.242
79	0.0145	38	0.1015	D	0.246
78	0.016	37	0.104	E	0.250
77	0.018	36	0.1065	F	0.257
76	0.020	35	0.110	G	0.261
75	0.021	34	0.111	H	0.266
74	0.0225	33	0.113	I	0.272
73	0.024	32	0.116	J	0.277
72	0.025	31	0.120	K	0.281
71	0.026	30	0.1285	L	0.290
70	0.028	29	0.136	M	0.295
69	0.0292	28	0.1405	N	0.302
68	0.031	27	0.144	O	0.316
67	0.032	26	0.147	P	0.323
66	0.033	25	0.1495	Q	0.332
65	0.035	24	0.152	R	0.339
64	0.036	23	0.154	S	0.348
63	0.037	22	0.157	T	0.358
62	0.038	21	0.159	U	0.368
61	0.039	20	0.161	V	0.377
60	0.040	19	0.166	W	0.386
59	0.041	18	0.1695	X	0.397
58	0.042	17	0.173	Y	0.404
57	0.043	16	0.177	Z	0.413

Figure 7.92 Drill sizes (American national standard).

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Drill	Decimal	Drill	Decimal	Drill	Decimal	Drill	Decimal	Drill	Decimal	Drill	Decimal
.35mm	.0138	1.75mm	.0650	3.70mm	.1457	6.40mm	.2520	9.00mm	.3543	17.00mm	.6693
.38mm	.0150	1.80mm	.0709	3.75mm	.1477	6.50mm	.2559	9.10mm	.3583	17.50mm	.6890
.40mm	.0157	1.85mm	.0728	3.80mm	.1496	6.60mm	.2598	9.20mm	.3622	18.00mm	.7087
.42mm	.0165	1.90mm	.0748	3.90mm	.1535	6.70mm	.2638	9.25mm	.3642	18.50mm	.7283
.45mm	.0177	1.95mm	.0768	4.00mm	.1575	6.75mm	.2658	9.30mm	.3661	19.00mm	.7480
.48mm	.0189	2.00mm	.0787	4.10mm	.1614	6.80mm	.2677	9.40mm	.3701	19.50mm	.7677
.50mm	.0197	2.05mm	.0807	4.20mm	.1654	6.90mm	.2716	9.50mm	.3740	20.00mm	.7874
.55mm	.0217	2.10mm	.0827	4.25mm	.1674	7.00mm	.2756	9.60mm	.3780	20.50mm	.8071
.60mm	.0236	2.15mm	.0846	4.50mm	.1771	7.10mm	.2795	9.70mm	.3819	21.00mm	.8268
.65mm	.0256	2.20mm	.0866	4.60mm	.1811	7.20mm	.2835	9.75mm	.3839	21.50mm	.8465
.70mm	.0276	2.25mm	.0886	4.70mm	.1850	7.25mm	.2855	9.80mm	.3558	22.00mm	.8661
.75mm	.0295	2.30mm	.0905	4.75mm	.1870	7.30mm	.2874	9.90mm	.3898	22.50mm	.8858
.80mm	.0315	2.35mm	.0925	4.80mm	.1890	7.40mm	.2913	10.00mm	.3937	23.00mm	.9055
.85mm	.0335	2.40mm	.0945	4.90mm	.1929	7.50mm	.2953	10.20mm	.4016	23.50mm	.9252
.90mm	.0354	2.45mm	.0965	5.00mm	.1968	7.60mm	.2992	10.50mm	.4134	24.00mm	.9449
.95mm	.0374	2.50mm	.0984	5.10mm	.2008	7.70mm	.3031	10.80mm	.4252	24.50mm	.9646
1.00mm	.0394	2.55mm	.1004	5.20mm	.2047	7.75mm	.3051	11.00mm	.4330	25.00mm	.9843
1.05mm	.0413	2.60mm	.1024	5.25mm	.2067	7.80mm	.3071	11.20mm	.4409		
1.10mm	.0433	2.65mm	.1043	5.30mm	.2087	7.90mm	.3110	11.50mm	.4528		
1.15mm	.0453	2.70mm	.1063	5.40mm	.2126	8.00mm	.3150	11.80mm	.4646	+1.00mm increments	
1.20mm	.0472	2.75mm	.1083	5.50mm	.2165	8.10mm	.3189	12.00mm	.4724	up to 48mm.	
1.25mm	.0492	2.80mm	.1102	5.60mm	.2205	8.20mm	.3228	12.20mm	.4803		
1.30mm	.0512	2.90mm	.1142	5.70mm	.2244	8.25mm	.3248	12.50mm	.4921	+5.00mm increments	
1.35mm	.0531	3.00mm	.1181	5.75mm	.2264	8.30mm	.3268	13.00mm	.5118	from 50mm up to	
1.40mm	.0551	3.10mm	.1220	5.80mm	.2283	8.40mm	.3307	13.50mm	.5315	105mm.	
1.45mm	.0571	3.20mm	.1260	5.90mm	.2323	8.50mm	.3346	14.00mm	.5512		
1.50mm	.0591	3.25mm	.1280	6.00mm	.2362	8.60mm	.3386	14.50mm	.5709		
1.55mm	.0610	3.30mm	.1299	6.10mm	.2401	8.70mm	.3425	15.00mm	.5906		
1.60mm	.0629	3.40mm	.1339	6.20mm	.2441	8.75mm	.3445	15.50mm	.6102		
1.65mm	.0650	3.50mm	.1378	6.25mm	.2461	8.80mm	.3465	16.00mm	.6299		
1.70mm	.0669	3.60mm	.1417	6.30mm	.2480	8.90mm	.3504	16.50mm	6496		

Figure 7.93 Drill sizes (metric).

Speeds, Feeds, Drill Geometry, and Cutting Recommendations for Standard Drill Types *

Material Type	Hardness Bhn	Tool grade	Drill type	PA-deg.	LRf deg.	HA-deg.	Point type	Speed, sfpm	Feed, ipr x 10^{-3}
Low-alloy steels	to 300	M-1, M-2	A	118-135	7-10	25-30	Split	50-60	3-7
4130, 4340, ,4140	300-400	M-1, M-2	A	118-135	7-10	25-30	split	40-50	2-6
	400-500	Cobalt	B	118-135	7-10	25-30	split	25-40	1-4
	over 500	C-2	C	118	7-10	0	notched	75-100	0.5-2
Die steels	to 300	M-1, M-2	A	118-135	7-10	25-30	split	45-55	3-7
Hot-work	300-400	M-1, M-2	A	118-135	7-10	25-30	split	35-50	2-6
	400-500	Cobalt	B	118-135	7-10	25-30	split	25-35	1-4
	over 500	C-2	C	118	7-10	0	Notched	70-90	0.5-2
Stainless steels (Austenitic) 300	135-185	M-1, M-2	A	118-135	7-10	25-30	split	70-90	2-6
Stainless steels	150-250	M-1, M-2	A	118-135	7-10	25-30	split	50-70	3-7
(Martensitic) 400	250-450	M-1, M-2	A	118-135	7-10	25-30	split	30-40	2-6
	over 450	Cobalt	B	118-135	7-10	25-30	split	20-30	1-4
Stainless steels	to 200	M-1, M-2	A	118-135	7-10	25-30	split	50-60	3-7
Precipitation	200-350	M-1, M-2	A	118-135	7-10	25-30	split	35-45	2-6
hardening 17-7PH, etc.	over 350	Cobalt	B	118-135	7-10	25-30	split	20-30	1-4
Nickel-cobalt steels	to 400	M-1, M-2	A	118-135	7-10	25-30	split	55-65	2-6
High-strength	400-500	Cobalt	B	118-135	7-10	25-30	split	30-40	1-4
	over 500	C-2	C	118	7-10	0	notched	70-90	0.5-2
High-temperature Cobalt-base alloys	to 300	Cobalt	B	118-135	7-10	25-30	split	15-25	1-4
High-temperature	to 250	Cobalt	B	118-135	7-10	25-30	split	20-30	2-6
Iron-base alloys	over 250	Cobalt	B	118-135	7-10	25-30	split	15-25	2-6
High-temperature	to 265	Cobalt	B	118-135	7-10	25-30	split	20-30	2-6
Nickel-base alloys	265-330	Cobalt	B	118-135	7-10	25-30	split	20-25	2-5
	over 330	Cobalt	B	118-135	7-10	25-30	split	15-20	1-4

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Magnesium & alloys	All	M-1, M-2	A	118-135	7-10	25-30	split	150-350	2-7
Aluminum & alloys 2024, 6061, 7075, etc.	All	M-1, M-2	A	118-135	7-10	25-30	split	175-400	2-7
Titanium	to 250	M-34, M-42	B	135	7-12	30-38	split	25-30	5-7
Titanium Alpha alloys	250-300	M-34, M-42	B	135	7-12	30-38	split	20-25	5-7
Titanium	to 350	M-34, M-42	B	135	7-12	30-38	split	20-25	5-7
Alpha-Beta alloys	over 350	M-34, M-42	B	135	7-12	30-38	split	15-25	5-7
Titanium	to 350	M-34, M-42	B	135	7-12	30-38	split	15-20	1-4
Beta alloys	over 350	M-34, M-42	B	135	7-12	30-38	split	15-17	0.5-2
Beryllium copper	250	C-2	D	90-118	10-15	25-30	split	30-45	2-8
Tungsten & alloys	to 350	C-2, C-3	D	90-118	7-10	25-30	notched	200-250	1-4
Brass, free-machining	All	M-1, M-2	A	118	7-10	25-30	standard	100-250	4-10
Bronzes, common	All	M-1, M-2	A	118	7-10	25-30	standard	200-250	3-15
Bronze, phosphur	Hard	M-1, M-2	A	118	7-10	25-30	notched	75-150	2-6
Copper	All	M-1, M-2	A	90-118	7-10	25-30	standard	100-250	1-5
Cast iron Soft to medium	soft-med.	M-1, M-2	A	118	7-10	25-30	std or split	75-150	2-8
Cast iron Hard	Hard	C-2	D	118	7-10	25-30	std or split	40-75	1-5
Zinc	All	M-1, M-2	A	118	7-10	25-30	standard	200-250	3-10
Low-carbon steels	to 300	M-1, M-2	A	118	7-10	25-30	standard	80-100	3-10
Thermoplastics	Medium	M-1, M-2	E	60-90	12-16	17	standard	100-150	2-15

Figure 7.94 Drilling recommendation table.

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Thermosetting plastics	Soft	M-1, M-2	E	60-90	12-16	17	standard	150	3-8
	Hard	M-1, M-2	E	60-90	12-16	17	standard	100	2-6

NOTE:
Drill Types: A = AIAA type B or C; B = Heavy duty cobalt; C = Carbide tipped; D = Solid carbide; E = Standard with wide, polished flutes.

Coolants and cutting fluids are recommended in the Coolant & Cutting Fluid Section of the handbook.

* Tabular data in the table is for drills of 0.125 through 0.500" diameter and hole depths of 1 to 3 drill diameters.
Adjustments must be made for other conditions, by interpolation or trial drilling. (Smaller drills have a lower ipr feed rate; larger drills have a higher ipr feed rate).

Drill geometry: PA = Point angle, degrees; LRf = Lip relief angle, degrees; HA = helix angle, degrees

Tabular data for ipr - Feed is given in powers of ten notation, i.e. 2 = .002"; 6 = .006"; 0.5 = 0.0005", etc.

Figure 7.94 (*Continued*)

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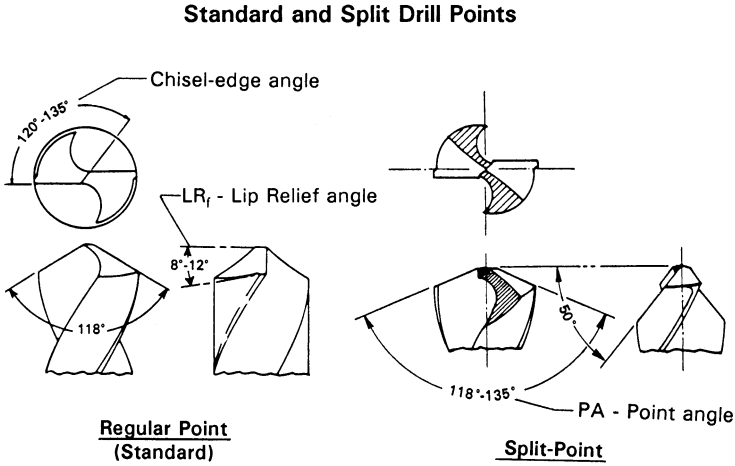

Figure 7.95 Standard and split points.

including core drilling, counterboring, and bottoming to a flat or other shape. The spade drill consists of the spade drill bit and holder. The holder may contain coolant holes through which coolant can be delivered to the cutting edges, under pressure, which cools the spade and flushes the chips from the drilled hole. Typical spade drills, holders, and terminology and spade geometry are shown in Fig. 7.96.

The standard point angle on a spade drill is 130°. The rake angle ranges from 10° to 12° for average-hardness materials. The rake angle should be 5° to 7° for hard steels and 15° to 20° for soft, ductile materials. The back-taper angle should be 0.001 to 0.002 in per inch of blade depth. The outside diameter clearance angle is generally between 7° and 10°.

The cutting speeds for spade drills are normally 10 to 15 percent lower than those for standard twist drills. See the tables of drill speeds and feeds in the preceding section for approximate starting speeds. Heavy feed rates should be used with spade drilling. The table shown in Fig. 7.97 gives recommended feed rates for spade drilling various materials.

Horsepower and thrust forces for spade drilling. The following simplified equations will allow you to calculate the approximate horse-

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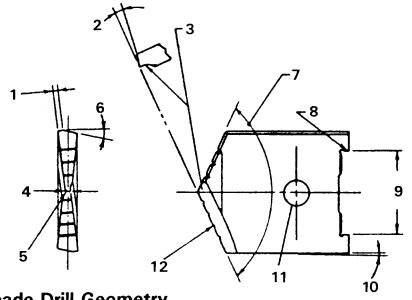
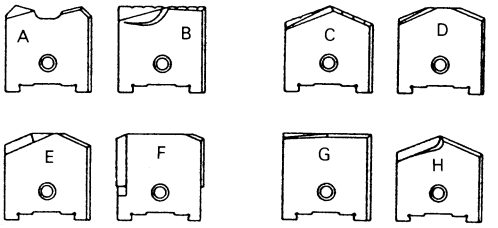
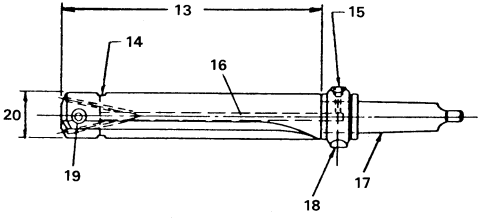


Spade Drill Geometry



Spade Drill Types

1- Circular OD land, radial land or margin
2- Front clearance/lip relief
3- Chip curler/gullet
4- Web
5- Chisel edge
6- OD clearance/radial relief
7- Point angle
8- Locating ears
9- Locating slot
10- Back taper
11- Screw hole
12- Chipbreaker grooves
13- Flute length
14-Locating flats
15- Coolant inlet (pipe thread)
16- Coolant holes
17- Shank
18- Coolant inductor
19- Blade screw
20- Body diameter



Spade Drill Holder

A- Spur-core blade
B- Facing blade (flat bottom)
C- Regular blade
D- Standard core blade
E- Standard carbide core blade
F- Core blade with carbide edges
G- Counterbore
H- Regular carbide blade

Figure 7.96 Spade drills.

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power requirements and thrust needed to spade drill various materials with different diameter spade drills. In order to do this, you must find the feed rate for your particular spade drill diameter, as shown in Fig. 7.97, and then select the P factor for your material, as tabulated in Fig. 7.98.

The following equations then may be used to estimate the required horsepower at the machine's motor and the thrust required in pounds force for the drilling process.

$$C_{\text{hp}} = P\left(\frac{\pi D^2}{4}\right)FN$$

$$T_p = 148{,}500PFD$$

$$M_{\text{hp}} = \frac{C_{\text{hp}}}{e}$$

$$F = \frac{f_m}{N} \qquad \text{and} \qquad f_m = FN$$

where C_{hp} = horsepower at the cutter
M_{hp} = required motor horsepower
T_p = thrust for spade drilling, pounds force
D = drill diameter, in
F = feed, ipr (see Fig. 7.97 for ipr/diameter/material)
P = power factor constant (see Fig. 7.98)
f_m = feed, ipm
N = spindle speed, rpm
e = drive motor efficiency factor (0.90 for direct belt drive to the spindle; 0.80 for geared head drive to the spindle)

Note: The P factors must be increased by 40 to 50 percent for dull tools, although dull cutters should not be used if productivity is to remain high.

7.3.8 Microdrills

Drills below 0.020 in in diameter are considered to be microdrills. Microdrills as small as 0.0016 in in diameter are available as stock items from the drill supply vendors. Microdrills are manufactured from HSS, cobalt-base carbides, and solid-tungsten carbides, and a limited selection is available in diamond and CBN surfaces. Some

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Recommended Feed Rates for Spade Drilling- (ipr, inches per revolution)

Material	Hardness Bhn	Feed - ipr Spade Drill Diameter, inches					
		1-1.25	1.25-2	2-3	3-4	4-5	5-8
Plain carbon steels	100-225	.012	.015	.018	.022	.025	.030
	225-275	.010	.013	.015	.018	.020	.025
	275-325	.008	.010	.013	.015	.018	.020
Free-machining steels	100-240	.014	.016	.018	.022	.025	.030
	240-325	.010	.014	.016	.020	.022	.025
Free-machining alloy steels	150-250	.014	.016	.018	.022	.025	.030
	250-325	.012	.014	.016	.018	.020	.025
	325-375	.010	.012	.014	.016	.018	.020
Alloy steels	125-180	.012	.015	.018	.022	.025	.030
	180-225	.010	.012	.016	.018	.022	.025
	225-325	.009	.010	.013	.015	.018	.020
	325-400	.006	.006	.010	.012	.014	.016
Grey cast iron	110-160	.020	.022	.026	.028	.030	.034
	160-240	.012	.014	.016	.018	.020	.022
	240-325	.010	.012	.016	.018	.018	.018
Ductile & nodular iron	140-190	.014	.016	.018	.020	.022	.024
	190-250	.012	.014	.016	.018	.018	.020
	250-325	.010	.012	.016	.018	.018	.018
Malleable iron- ferritic	110-160	.014	.016	.018	.020	.022	.024
Malleable iron- pearlitic	160-280	.011	.013	.015	.018	.018	.018
Stainless steels- free-machining							
Ferritic & austenitic (screw stock)	-------	.016	.018	.020	.022	.024	.026
Martensitic (440F, etc.)	-------	.012	.014	.016	.016	.018	.020

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Stainless steels							
Ferritic & austenitic (200 & 300 series)	-------	.012	.014	.016	.018	.020	.020
Martensitic (400 series)	-------	.010	.012	.012	.014	.016	.018
Copper alloys							
Soft (ETP-110, etc)	-------	.016	.018	.020	.026	.028	.030
Hard (bronzes)	-------	.010	.012	.014	.016	.018	.018
Aluminum alloys (free-machining)	-------	.020	.022	.024	.028	.030	.040
Magnesium alloys (general) **	-------	.024	.026	.030	.034	.040	.050
High-temperature alloys (general)	-------	.008	.010	.012	.012	.014	.014
Titanium alloys (general)	-------	.008	.010	.012	.014	.014	.016
Tool steels							
Water-hardening & shock resisting	150-250	.012	.-14	.016	.018	.020	.022
Cold work	200-250	.007	.008	.009	.010	.011	.012
Hot work	150-250	.012	.013	.015	.016	.018	.020
High-speed steels	200-250	.010	.012	.013	.015	.017	.018

NOTE: Hardness ranges are Brinell hardness numbers. Tabular data is in inches of feed per revolution, ipr.
** A fire hazard exists when machining or drilling magnesium & alloys.

Figure 7.97 Feed rates for spade drills.

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"P" Factors for Spade Drilling Various Materials

Material	Hardness Bhn	"P" Factor
Plain carbon & alloy steels	90-200	0.75
	200-275	0.92
	300-375	1.02
	375-450	1.18
	45-52R_C	1.45
Gray cast irons	-------	0.25
Alloy cast irons & ductile irons	-------	0.50
Stainless steel (austenitic)	-------	0.96
Stainless steels (martensitic)	-------	0.81
Titanium alloys	-------	0.87
Aluminum alloys	-------	0.20
Magnesium alloys	-------	0.15
Copper alloys	Soft - R_B 20-80	0.42
	Hard - R_B 80-100	0.75
Tool steels	-------	1.10
Cobalt based alloys	-------	1.25
High-temperature alloys	-------	1.45
Non-ferrous free-machining alloys	-------	0.45

Note: Where no hardness range is given, the maximum hardness is 300 Bhn. For harder materials, use a higher "P" factor.

Figure 7.98 *P*-factor table.

of the standard commercially available microdrill sizes are listed in Fig. 7.99.

In order to use microdrills, special machines have been developed for controlling these extremely small and fragile tools. Holes of great precision may be made in many materials using the appropriate machine tools and drills designed for microdrilling.

Needless to say, a microdrilling operation is conducted under a high-magnification viewing device, with the hand motions of the

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Standard Size Microdrills - High-Speed Steel and Cobalt

High-Speed Steel Microdrills

Diameter inches	mm	Flute lth.
0.0059	0.15	0.0469
0.0063	0.16	0.0469
0.0067	0.17	0.0625
0.0071	0.18	0.0625
0.0075	0.19	0.0625
0.0079	0.20	0.0625
0.0083	0.21	0.0625
0.0087	0.22	0.0625
0.0091	0.23	0.0625
0.0094	0.24	0.0781
0.0098	0.25	0.0781
0.0102	0.26	0.0781
0.0106	0.27	0.0781
0.0110	0.28	0.0938
0.0114	0.29	0.0938
0.0118	0.30	0.0938
0.0126	0.32	0.0938
0.0134	0.34	0.0938
0.0142	0.36	0.1875
0.0150	0.38	0.1875
0.0157	0.40	0.1875
0.0165	0.42	0.1875
0.0173	0.44	0.1875
0.0181	0.46	0.1875
0.0189	0.48	0.1875
0.0197	0.50	0.1875

Note: Drill points are 118°. Shank size is same as drill diameter. Drills 0.38mm and less are 0.75" long, all others 0.875".

Cobalt Microdrills

Diameter inches	mm	Flute lth.
0.0019	0.05	0.0158
0.0024	0.06	0.0158
0.0028	0.07	0.0158
0.0032	0.08	0.0197
0.0035	0.09	0.0197
0.0039	0.10	0.0276
0.0043	0.11	0.0276
0.0047	0.12	0.0276
0.0051	0.13	0.0394
0.0055	0.14	0.0394
0.0059	0.15	0.0394
0.0063	0.16	0.0552
0.0067	0.17	0.0552
0.0071	0.18	0.0552
0.0075	0.19	0.0552
0.0079	0.20	0.0709
0.0083	0.21	0.0709
0.0087	0.22	0.0709
0.0091	0.23	0.0709
0.0094	0.24	0.0709
0.0098	0.25	0.0867
0.0102	0.26	0.0867
0.0106	0.27	0.0867
0.0110	0.28	0.0867
0.0114	0.29	0.0867
0.0118	0.30	0.0867
0.0122	0.31	0.1103
0.0126	0.32	0.1103
0.0130	0.33	0.1103
0.0134	0.34	0.1103
0.0138	0.35	0.1103
0.0142	0.36	0.1103
0.0146	0.37	0.1103
0.0150	0.38	0.1103
0.0154	0.39	0.1142
0.0157	0.40	0.1142
0.0161	0.41	0.1142
0.0165	0.42	0.1142
0.0169	0.43	0.1142
0.0173	0.44	0.1142
0.0177	0.45	0.1142
0.0181	0.46	0.1142
0.0185	0.47	0.1142
0.0189	0.48	0.1142
0.0193	0.49	0.1576
0.0197	0.50	0.1576

Note: Cobalt drills are for extremely accurate drilling jobs. Right hand spiral, 118° points and 25° helix angle. All shank diameters are 1mm and total length 25mm.

Figure 7.99 Microdrills.

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operator greatly reduced in magnitude by linkage translators on the microdrilling machine.

Specialty flat-style microdrill geometry and terminology are shown in Fig. 7.100, together with the various types of microdrilling tools. The microdrilled hole usually requires additional operations such as countersinking, reaming, counterboring, etc. Figure 7.101 gives the preferred dimensions for the special flat-type microdrills that usually are custom made for various applications. Materials for these special microdrills may be HSS, cobalt-base carbides, or tungsten carbides.

Solid-carbide square die drills. For cold drilling extremely accurate holes in hard steels from Rockwell C 40 to C 70, the carbide square die drill is standardized in sizes from 0.09375 through 0.5000 in in diameter. These are available from national drill distributors and are ideally suited for mold and die repair and maintenance.

7.3.9 Drilling problems and solutions

Problem	Causes	Remedy
Outer corners breakdown	Revolutions per minute too high	Reduce feed and speed
	Poor lip relief	Check lip relief
Cutting lips chip	Feed too high	Reduce feed
	High lip relief	Check lip relief
Cracks in cutting lips	Running too hot	Repoint drill
		Check feed and speed
Drill breaks	Improper point	Use proper point
	Flutes clogging	Check feed
Drill splits up center	Feed too high	Reduce feed
	Lip relief wrong	Correct relief
Drill will not penetrate	Reverse chisel	Check chisel angle
Rough hole	Dull point	Repoint drill
	No lubricant	Use lubricant
Oversize hole	Unequal length on cutting lips	Repoint drill
Loose spindle		Inspect spindle
Chips change form while drilling	Improper point	Repoint drill
Margins chip	Oversize bushing	Change bushing

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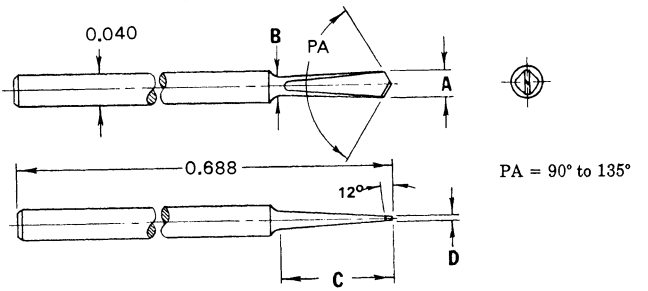
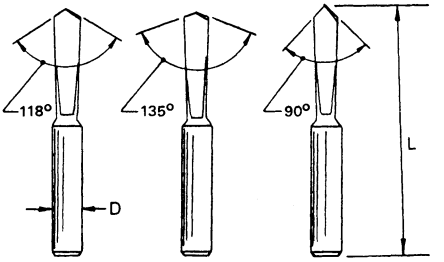
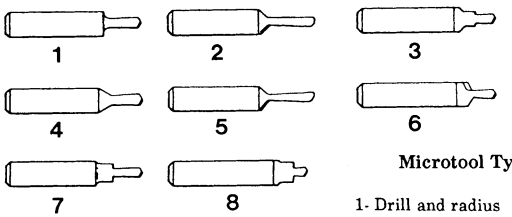


Flat Microdrill Geometry

(See Figure 7.101 for dimensions)





Microtools

Microtool Types

1- Drill and radius
2- Reamer and countersink
3- Drill, counterbore and countersink
4- Drill and countersink
5- Reamer and radius
6- Drill, radius and countersink
7- Drill and counterbore
8- Drill, counterbore and radius

Microdrills and Microtools

Figure 7.100 Geometry of microdrills and microtools.

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Flat Microdrill Dimensions - Refer to Figure 7.100 for drill geometry.

Diameter A	Back Taper B	Length C	Web Thickness D
0.0010	0.0001	0.0070	0.0005-0.00075
0.0020	0.0001	0.0140	0.0011-0.0015
0.0030	0.0002	0.0210	0.0016-0.0020
0.0040	0.0002	0.0280	0.0018-0.0022
0.0050	0.0003	0.0350	0.0020-0.0024
0.0060	0.0003	0.0420	0.0022-0.0026
0.0070	0.0004	0.0490	0.0024-0.0028
0.0080	0.0004	0.0560	0.0026-0.0030
0.0090	0.0005	0.0630	0.0028-0.0032
0.0100	0.0005	0.0700	0.0030-0.0034
0.0110	0.0006	0.0770	0.0032-0.0036
0.0120	0.0006	0.0840	0.0038-0.0042
0.0130	0.0007	0.0910	0.0042-0.0046
0.0140	0.0007	0.0980	0.0044-0.0048
0.0150	0.0008	0.1050	0.0046-0.0050
0.0160	0.0008	0.1120	0.0048-0.0052
0.0170	0.0009	0.1190	0.0050-0.0054
0.0180	0.0009	0.1260	0.0053-0.0058
0.0190	0.0010	0.1330	0.0056-0.0060
0.0200	0.0010	0.1400	0.0060-0.0064

Note: These microdrill sizes and dimensions are for custom made flat microdrills.
See Figure 7.99 for modern standard size microdrills of HSS and cobalt alloy.

Figure 7.101 Flat microdrill dimensions.

7.4 Reaming

A reamer is a rotary cutting tool, either cylindrical or conical in shape, used for enlarging drilled holes to accurate dimensions, normally on the order of ±0.0001 in and closer. Reamers usually have two or more flutes that may be straight or spiral in either left-hand or right-hand spiral. Reamers are made for manual or machine operation. Figure 7.102 shows reamer geometry and terminology.

Reamers are made in various forms, including

- Hand reamers
- Machine reamers
- Left-hand flute
- Right-hand flute
- Expansion reamers
- Chucking reamers

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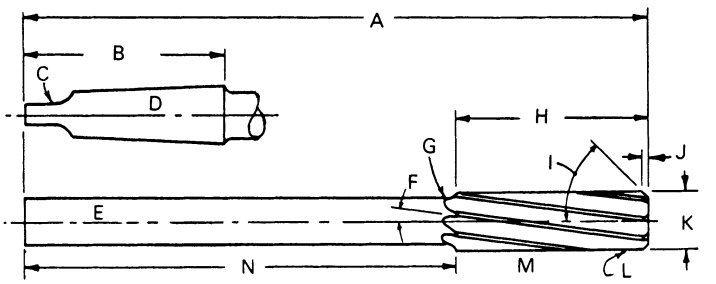
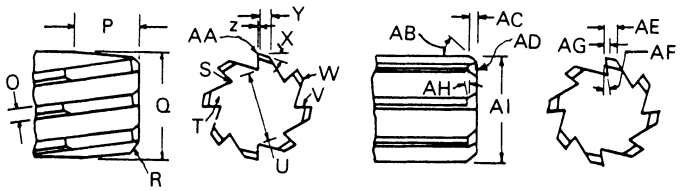
Reamer Features



Chucking Reamer - Straight & Taper Shank



Hand Reamer Machine Reamer

A Overall length
B Shank length
C Tang
D Taper shank
E Straight shank
F Helix angle
G Cutter sweep
H Flute length
I Chamfer angle
J Chamfer length
K Actual size
L Body
M Helix flutes, Right hand shown
N Shank length
O Land width
P Starting taper
Q Actual size diameter
R Bevel
S Flute
T Land
U Core diameter
V Cutting face
W Heel
X Relief angle
Y Relieved land
Z Margin
AA Cutting edge
AB Chamfer angle
AC Chamfer length
AD Chamfer relief
AE Land width
AF Radial rake angle
AG Margin
AH Chamfer relief angle
AI Actual size diameter

Figure 7.102 Reamer features.

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- Stub screw-machine reamers
- End-cutting reamers
- Jobber reamers
- Shell reamers
- Combined drill and reamer

Most reamers are produced from premium-grade HSS. Reamers are also produced in cobalt alloys, and these may be run at speeds 25 percent faster than HSS reamers. Reamer feeds depend on the type of reamer, the material and amount to be removed, and the final finish required. Material-removal rates depend on the size of the reamer and material, but general figures may be used on a trial basis and are summarized below:

Hole diameter	Material to be removed
Up to 0.500 in diameter	0.005 in for finishing
More than 0.500 in diameter	0.015 in for finishing
Up to 0.500 in diameter	0.015 in for semifinished holes
More than 0.500 in diameter	0.030 in for semifinished holes

This is an important consideration when using the expansion reamer owing to the maximum amount of expansion allowed by the adjustment on the expansion reamer.

7.4.1 Machine speeds and feeds for HSS reamers

Note: Cobalt alloy and carbide reamers may be run at speeds 25 percent faster than those shown in Fig. 7.103.

Carbide-tipped and solid-carbide chucking reamers are also available and afford greater effective life than HHS and cobalt reamers without losing their nominal size dimensions. Speeds and feeds for carbide reamers generally are similar to those for the cobalt alloy types.

7.4.2 Sharpening reamers

It would be difficult, if not impossible, to hand sharpen any type of reamer. Reamer sharpening machines are produced by various man-

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Machine Speeds and Feeds for HSS Reamers- (sfpm and ipr)

Material	Speed (sfpm)	Feed Code (ipr)
Steel - 150 Bhn	80	1
Steel - 200 Bhn	55	2
Steel - 250 Bhn	35	3
Steel - 300 Bhn	30	3
Steel - 350 Bhn	17	4
Steel - 400 Bhn	10	4
Steel, cast	25	3
Steel, forged alloys	30	3
Steel, low carbon	75	2
Steel, high carbon	45	4
Steel, stainless	15	3
Steel, tool	35	4
Titanium	40	1
Zinc alloy	150	1
Aluminum & alloys	150	1
Brass, leaded	175	1
Brass, red & yellow	150	1
Bronzes	160	1
Copper	45	3
Cast iron, chilled	10	4
Cast iron, hard	50	3
Cast iron, pearlitic	60	1
Cast iron, soft	95	1
Malleable iron	65	2
Monels	30	3
Nickels	40	3
Plastic, hard	50	1
Plastic, soft	65	3

Feed Code, ipr (inches per revolution)

Reamer Diameter	Code 1	Code 2	Code 3	Code 4
0.125"	0.006	0.005	0.004	0.003
0.500"	0.012	0.010	0.007	0.005
1.00"	0.020	0.015	0.012	0.008
2.00"	0.032	0.025	0.020	0.012
2.25 - 2.50"	0.043	0.035	0.028	0.018
2.75 - 3.00"	0.055	0.045	0.035	0.024

Note: Reamer feeds may be interpolated for intermediate sizes than those shown in the table. Cobalt reamers may be run at speeds 25% faster than those shown in the table for HSS.

Figure 7.103 Speeds and feeds for HSS reamers.

ufacturers (Darex), and sharpening facilities are available nationwide for this purpose.

Standard reamer sizes are produced and may be purchased separately or in sets for various applications. Some of the more common types of reamers are shown in Fig. 7.104.

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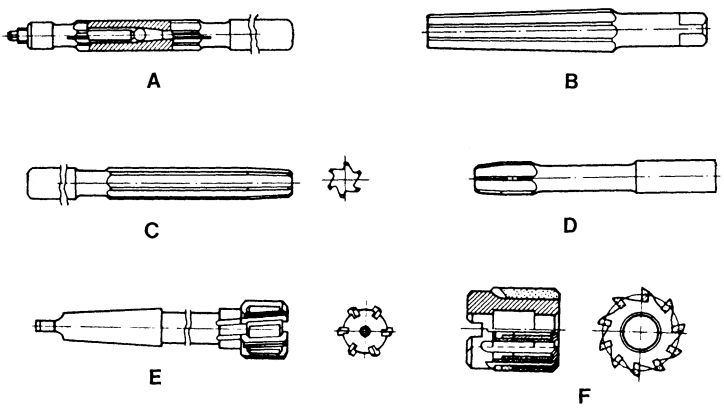

A Expansion Reamer
B Taper Reamer
C Hand Reamer
D Machine Reamer
E Inserted Blade Reamer
F Shell Reamer

Figure 7.104 Reamer types.

7.4.3 Forms of reamers

Other forms of reamers include the following:

Morse taper reamers. These reamers are used to produce and maintain holes for American standard Morse taper shanks. They usually come in a set of two, one for roughing and the other for finishing the tapered hole.

Taper-pin reamers. Taper-pin reamers are produced in HSS with straight, spiral, and helical flutes. They range in size from pin size 7/0 through 14 and include 21 different sizes to accommodate all standard taper pins.

Dowel-pin reamers. Dowel-pin reamers are produced in HSS for standard length and jobber's lengths in 14 different sizes from 0.125 through 0.500 in. The nominal reamer size is slightly smaller than the pin diameter to afford a force fit.

Helical-flute die-maker's reamers. These reamers are used as milling cutters to join closely drilled holes. They are produced from HSS and are available in 16 sizes ranging from size AAA through O.

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Reamer blanks. Reamer blanks are available for use as gauges, guide pins, or punches. They are made of HSS in jobber's lengths from 0.015 through 0.500 in in diameter. Fractional sizes through 1.00 in in diameter and wire-gauge sizes also are available.

Shell reamers (see Fig. 7.104*f*). These reamers are designed for mounting on arbors and are best suited for sizing and finishing operations. Most shell reamers are produced from HSS. The inside hole in the shell reamer is tapered ⅛ in per foot and fits the taper on the reamer arbor.

Expansion reamers (see Fig. 7.104*a*). The hand expansion reamer has an adjusting screw at the cutting end that allows the reamer flutes to expand within certain limits. The recommended expansion limits are listed below for sizes through 1.00 in in diameter:

Reamer size: 0.25 to 0.625 in diameter Expansion limit = 0.010 in

Reamer size: 0.75 to 1.000 in diameter Expansion limit = 0.013 in

Note: Expansion reamer stock sizes up to 3.00 in in diameter are available.

7.5 Broaching

Broaching is a precision machining operation wherein a broach tool is either pulled or pushed through a hole in a workpiece or over the surface of a workpiece to produce a very accurate shape such as round, square, hexagonal, spline, keyway, and so on. Keyways in gear and sprocket hubs are broached to an exact dimension so that the key will fit with very little clearance between the hub of the gear or sprocket and the shaft. The cutting teeth on broaches are increased in size along the axis of the broach so that as the broach is pushed or pulled through the workpiece, a progressive series of cuts is made to the finished size in a single pass.

Broaches are driven or pulled by manual arbor presses and horizontal or vertical broaching machines. A single stroke of the broaching tool completes the machining operation. Broaches are commonly made from premium-quality HSS and are supplied either in single tools or as sets in graduated sizes and different shapes. Figure 7.105 shows a number of different types of broaches such as keyway, square, and hexagonal.

Broaches may be used to cut internal or external shapes on workpieces. Blind holes also can be broached with specially designed

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Figure 7.105 Keyway, square, and hexagonal broaches.

broaching tools. The broaching tool teeth along the length of the broach normally are divided into three separate sections. The teeth of a broach include roughing teeth, semifinishing teeth, and finishing teeth. All finishing teeth of a broach are the same size, whereas the semifinishing and roughing teeth are progressive in size up to the finishing teeth.

Figure 7.106 shows the terminology and geometry of broaching teeth. A broaching tool must have sufficient strength and stock-removal and chip-carrying capacity for its intended operation. An interval-pull broach must have sufficient tensile strength to withstand the maximum pulling forces that occur during the pulling operation. An internal-push broach must have sufficient compressive strength, as well as the ability to withstand buckling or breaking, under the pushing forces that occur during the pushing operation.

Broaches are produced in sizes ranging from 0.050 in to as large as 20 in or more. The term *button broach* was used for broaching tools that produced the spiral lands that form the "rifling" in gun barrels from small to large caliber. Broaches may be rotated to produce a predetermined spiral angle during the pull or push operations.

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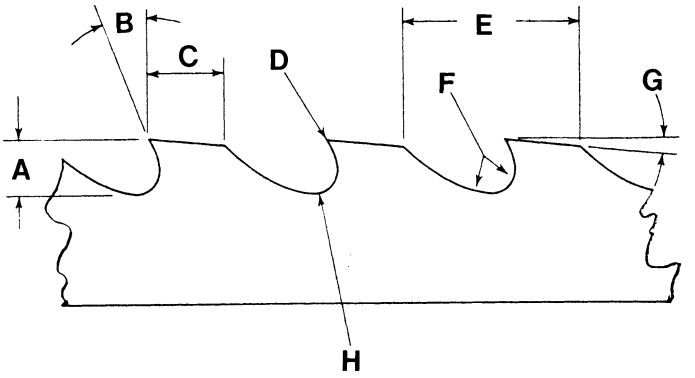

Broach Terminology and Geometry

A	Gullet Depth	E	Pitch
B	Face Angle	F	Tooth Gullet
C	Land	G	Rake Angle
D	Cutting Edge	H	Root Radius

Figure 7.106 Broach terminology.

7.5.1 Calculation of pull forces during broaching

The allowable pulling force P is determined by first calculating the cross-sectional area at the minimum root of the broach. The allowable pull in pounds force is determined from

$$P = \frac{A_r F_y}{f_s}$$

where A_r = minimum tool cross section, in^2
F_y = tensile yield strength or yield point of tool steel, psi
f_s = factor of safety (generally 3 for pull broaching)

The minimum root cross section for a round broach is

$$A_r = \frac{\pi D_r^2}{4} \qquad \text{or} \qquad 0.7854 D_r^2$$

where D_r is the minimum root diameter in inches. The minimum pull-end cross section A_p is

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$$A_p = \frac{\pi}{4} D_p^2 - WD_p \qquad \text{or} \qquad 0.7854 D_p^2 - WD_p$$

where D_p = pull-end diameter, in
W = pull-slot width, in

7.5.2 Calculation of push forces during broaching

Knowing the length L and the compressive yield point of the tool steel used in a broach, the following relations may be used in designing or determining the maximum push forces allowed in push broaching. If the length of the broach is L and the minimum tool diameter is D_r, the ratio L/D_r should be less than 25 so that the tool will not bend under maximum load. Most push broaches are short enough that the maximum compressive strength of the broach material will allow much greater forces than the forces applied during the broaching operation.

If the L/D_r ratio is greater than 25, compressive broaching forces may bend or break the broach tool if they exceed the maximum allowable force for the tool. The maximum allowable compressive force (pounds force) for a long push broach is determined from the following equation:

$$P = \frac{5.6 \times 10^7 D_r^4}{(f_s) L^2}$$

where L is measured from the push end to the first tooth in inches.

7.5.3 Minimum forces required for broaching different materials

For flat-surface broaches,

$$F = WnR\psi$$

For round-hole internal broaches,

$$F = \frac{\pi DnR}{2}\psi$$

For spline-hole broaches,

$$F = \frac{nSWR}{2}\psi$$

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where F = minimum pulling or pushing force required, lbf (pounds force)
W = width of cut per tooth or spline, in
D = hole diameter before broaching, in
R = rise per tooth, in
n = maximum number of broach teeth engaged in the workpiece
S = number of splines (for splined holes only)
ψ = broaching constant (see Fig. 7.107 for values)

Referring to Fig. 7.106, typical rake and relief angles are specified in Figure 7.108.

7.6 Vertical Boring and Jig Boring

The increased demand for accuracy in producing large parts initiated the refined development of modern vertical and jig boring machines. Although the modern CNC machining centers can handle small to medium-sized jig boring operations, very large and heavy work of high precision is done on modern CNC jig boring machines or vertical boring machines. Also, any size work that requires extreme accuracy is usually jig-bored. The modern jig boring machines are equipped with high-precision spindles and x,y-coordinate table movements of high precision and may be CNC

Broaching Constants (ψ) for Various Materials

Material	Value of ψ
Aluminum	200,000 - 300,000
Babbitt	25,000 - 35,000
Brass	200,000 - 300,000
Bronze	300,000 - 350,000
Cast irons	200,000 - 350,000
High-temperature alloys	350,000 - 600,000
Mild steels	350,000 - 450,000
Steel castings	350,000 - 400,000
Titanium	325,000 - 375,000
Zinc alloys	200,000 - 250,000

Note: The tabular values given in the table have a limited value due to the many variables involved in broaching, such as chipbreakers, lubricating and cutting fluid effects and other factors which tend to increase or reduce the required cutting force as calculated using the preceding equations.

Figure 7.107 Broaching constants.

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Typical HSS Broach Rake Angles and Relief Angles - Degrees)

Material	Rake Angle (Degrees)	Relief Angle (Degrees)
Aluminum	6 - 10	------
Babbitt	8 - 10	------
Brass	-5 to 5	2 - 3
Bronze	0	1 - 2
Cast iron	6 - 10	2 - 5
Copper	12 - 15	2 - 3
Aluminum bronze	12 - 15	2 - 3
Steels: SAE		
1035	15	1 - 2
1112	15	2 - 3
4140	8 - 15	1 - 3
5140	18 - 20 (finishing)	1 - 2
Stainless steels: AISI		
303	15	0.5 - 2
304, 304L	15	0.5 - 2
316	12 - 15	0.5 - 2
410	12 - 15	0.5 - 2
430	15 - 20	0.5 - 2
440	12- 15	0.5 - 2
Titanium:		
Soft	5 - 15	2 - 4
Hard	12 - 15	2.5 - 3
Zinc	6	------

Figure 7.108 Broach rake angles.

controlled with digital readout panels. For a modern jig boring operation that is CNC/DNC controlled, the circle diameter and number of equally spaced holes or other geometric pattern are entered into the DNC program, and the computer calculates all the coordinates and orientation of the holes from a reference point. This information is either sent to the CNC jig boring machine's controller, or the machine operator can load this information into the controller, which controls the machine movements to complete the machining operation. A typical jig boring machine is illustrated in Fig. 7.109.

Extensive tables of jig boring coordinates are not necessary with the modern CNC jig boring or vertical boring machines. Figures 7.110 and 7.111 are for manually controlled machines, where the machine operator makes the movements and coordinate settings manually.

Vertical boring machines with tables up to 192 in in diameter are produced for machining very large and heavy workpieces. For manually controlled machines with vernier or digital readouts, a table

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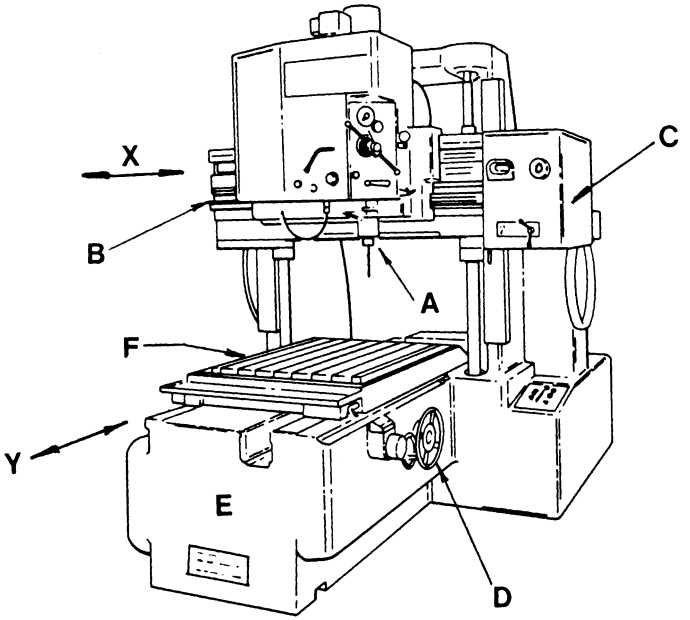

Typical Jig Boring Machine- NC or CNC

A High precision spindle
B X axis ways
C Controller
D Manual table positioning control
E Front
F Horizontal clamping table
X X axis movement
Y Y axis movement

Figure 7.109 Jig boring machine.

of jig boring dimensional coordinates is shown in Fig. 7.110 for dividing a 1-in circle into a number of equal divisions. Since the dimensions or coordinates given in the table are for *x,y* table movements, the machine operator may use these directly to make the appropriate machine settings after converting the coordinates for the required circle diameter to be divided.

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Jig Boring Coordinates for Dividing the Circle

Hole No.	Horizontal X	Vertical Y	Hole No.	Horizontal X	Vertical Y
Three holes:			Thirteen holes:		
1	0.50000		1	0.50000	
2	0.75000	0.43301	2	0.05727	0.23236
3	----------	0.86602	3, 13	0.15870	0.17913
Five holes:			4, 12	0.22376	0.08486
1	0.50000		5, 11	0.23757	0.02885
2	0.34549	0.47553	6, 10	0.19695	0.13594
3, 5	0.55902	0.18164	7, 9	0.11121	0.21190
4	----------	0.58778	8	----------	0.23932
Six holes:			Fourteen holes:		
1, 3, 6	0.50000		1	0.50000	
2, 4, 5	0.25000	0.43301	2, 8, 9	0.04951	0.21694
Seven holes:			3, 7, 10, 14	0.13875	0.17397
1	0.50000		4, 6, 11, 13	0.20048	0.09655
2	0.18826	0.39091	5, 12	0.22252	
3, 7	0.42300	0.09655	Fifteen holes:		
4, 6	0.33923	0.27052	1	0.50000	
5	----------	0.43388	2	0.04323	0.20337
Eight holes:			3, 15	0.12221	0.16820
1	0.50000		4,14	0.18005	0.10396
2, 5, 6	0.14645	0.35355	5, 13	0.20677	0.02173
3, 4, 7, 8	0.35355	0.14645	6, 12	0.19774	0.06425
Nine holes:			7, 11	0.15451	0.13912
1	0.50000		8, 10	0.08456	0.18994
2	0.11698	0.32139	9	----------	0.20790
3, 9	0.29620	0.17101	Sixteen holes:		
4, 8	0.33682	0.05939	1	0.50000	
5, 7	0.21084	0.26200	2, 9, 10	0.03806	0.19134
6	----------	0.34202	3, 8, 11, 16	0.10839	0.16221
Ten holes:			4, 7, 12, 15	0.16221	0.10839
1	0.50000		5, 6, 13, 14	0.19134	0.03806
2, 6, 7	0.09549	0.29389	Seventeen holes:		
3, 5, 8, 10	0.25000	0.18164	1	0.50000	
4,9	0.30902		2	0.03377	0.18062
Eleven holes:			3, 17	0.09672	0.15623
1	0.50000		4, 16	0.14664	0.11073
2	0.07937	0.27032	5, 15	0.17674	0.05028
3, 11	0.21292	0.18450	6, 14	0.18296	0.01695
4, 10	0.27887	0.04009	7, 13	0.16449	0.08190
5, 9	0.25626	0.11704	8, 12	0.12379	0.13580
6, 8	0.15233	0.23701	9, 11	0.06637	0.17134
7	----------	0.28172	10	----------	0.18374
Twelve holes:			Eighteen holes:		
1	0.50000		1	0.50000	
2, 7, 8	0.06699	0.25000	2, 10, 11	0.03016	0.17101
3, 6, 9, 12	0.18301	0.18301	3, 9, 12, 18	0.08682	0.15038
4, 5, 10, 11	0.25000	0.06699	4, 8, 13, 17	0.13302	0.11162
			5, 7, 14, 16	0.16318	0.05939
			6, 15	0.17364	

Figure 7.110 Jig boring coordinates.

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Jig Boring Coordinates for Dividing the Circle

Hole No.	Horizontal X	Vertical Y	Hole No.	Horizontal X	Vertical Y
Nineteen holes:			11, 15	0.07076	0.11634
1	0.50000		12, 14	0.03673	0.13112
2	0.02709	0.16235	13	----------	0.13616
3, 10	0.07834	0.14475	Twenty-four holes:		
4, 18	0.12110	0.11148	1	0.50000	
5, 17	0.15073	0.06612	2, 13, 14	0.01704	0.12941
6, 16	0.16403	0.01358	3, 12, 15, 24	0.04995	0.12059
7, 15	0.15956	0.04039	4, 11, 16, 23	0.07946	0.10355
8, 14	0.13779	0.09003	5, 10, 17, 22	0.10355	0.07946
9, 13	0.10110	0.12989	6, 9, 18, 21	0.12059	0.04995
10, 12	0.05344	0.15567	7, 8, 19, 20	0.12941	0.01704
11	----------	0.16460	Twenty-five holes:		
Twenty holes:			1	0.50000	
1	0.50000		2	0.01508	0.12434
2, 11, 12	0.02447	0.15451	3, 25	0.04677	0.11653
3, 10, 13, 20	0.07102	0.13938	4, 24	0.07367	0.10140
4, 9, 14, 19	0.11062	0.11062	5, 23	0.09657	0.07989
5, 8, 15, 18	0.13938	0.07102	6, 22	0.11340	0.05337
6, 7, 16, 17	0.15451	0.02447	7, 21	0.12312	0.02348
Twenty-one holes:			8, 20	0.12508	0.00787
1	0.50000		9, 19	0.11920	0.03873
2	0.02221	0.14738	10, 15	0.10582	0.06716
3, 21	0.06467	0.13428	11, 17	0.08580	0.09136
4, 20	0.10138	0.10925	12, 16	0.06038	0.10983
5, 19	0.12908	0.07452	13, 15	0.03116	0.12140
6, 18	0.14530	0.03317	14	----------	0.12532
7, 17	0.14862	0.01114	Twenty-six holes:		
8, 16	0.13874	0.05445	1	0.50000	
9, 15	0.11652	0.09293	2, 14, 15	0.01454	0.11966
10, 14	0.08397	0.12314	3, 13, 16, 26	0.04273	0.11270
11, 13	0.04393	0.14242	4, 12, 17, 25	0.06848	0.09920
12	----------	0.14904	5, 11, 18, 24	0.09022	0.07993
Twenty-two holes:			6, 10, 19, 23	0.10673	0.05601
1	0.50000		7, 9, 20, 22	0.11703	0.02885
2, 12, 13	0.02025	0.14086	8, 21	0.12054	
3, 11, 14, 22	0.05912	0.12946	Twenty-seven holes		
4, 10, 15, 21	0.09321	0.10755	1	0.50000	
5, 9, 16, 20	0.11971	0.07695	2	0.01348	0.11530
6, 8, 17, 19	0.13655	0.04009	3, 27	0.03971	0.10910
7, 18	0.14232		4, 26	0.06379	0.09699
Twenty-three holes:			5, 25	0.08444	0.07967
1	0.50000		6, 24	0.10054	0.05805
2	0.01854	0.13490	7, 23	0.11121	0.03329
3, 23	0.05425	0.12480	8, 22	0.11580	0.00675
4, 22	0.08593	0.10562	9, 21	0.11433	0.02016
5, 21	0.11125	0.07853	10, 20	0.10660	0.04598
6, 20	0.12830	0.04560	11, 19	0.09312	0.06933
7, 19	0.13585	0.00930	12, 18	0.07462	0.08893
8, 18	0.13331	0.02771	13, 17	0.05210	0.10374
9, 17	0.12091	0.06264	14, 16	0.02678	0.11297
10, 16	0.09951	0.09295	15	----------	0.11608

Figure 7.110 (*Continued*)

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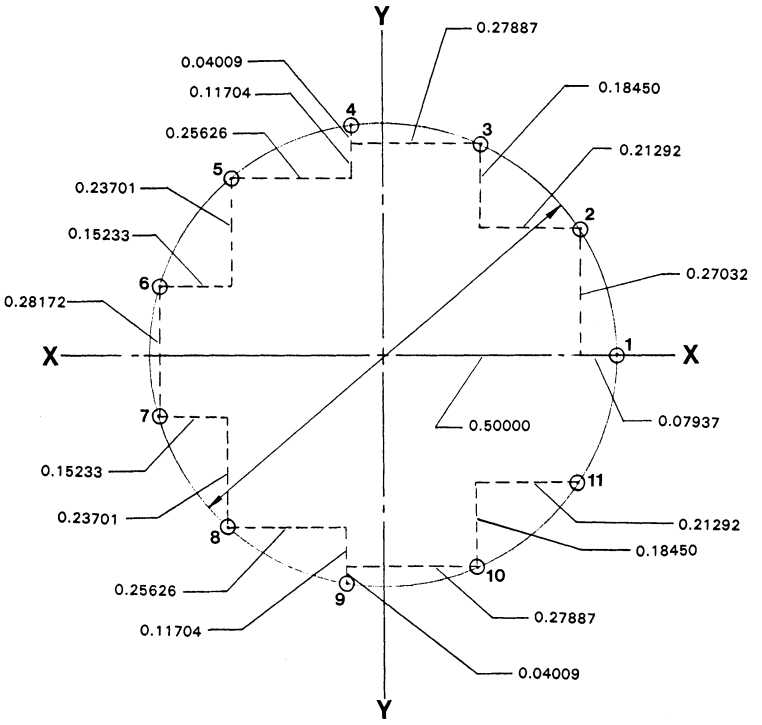

Figure 7.111 Coordinate diagram.

Figure 7.111 is a coordinate diagram of a jig bore layout for 11 equally spaced holes on a 1-in-diameter circle. The coordinates are taken from the table in Fig. 7.110. If a different-diameter circle is to be divided, simply multiply the coordinate values in the table by the diameter of the required circle; i.e., for an 11-hole circle of 5-in diameter, multiply the coordinates for the 11-hole circle by 5. Thus the first hole x dimension would be $5 \times 0.50000 = 2.50000$ in, and so on. Figure 7.112 shows a typical boring head for removable inserts.

7.7 Grinding, Lapping, Honing, and Superfinishing (Surface Finishes)

7.7.1 Grinding

The grinding process is an abrasive machining operation where material is removed from a workpiece in small chips or particles by

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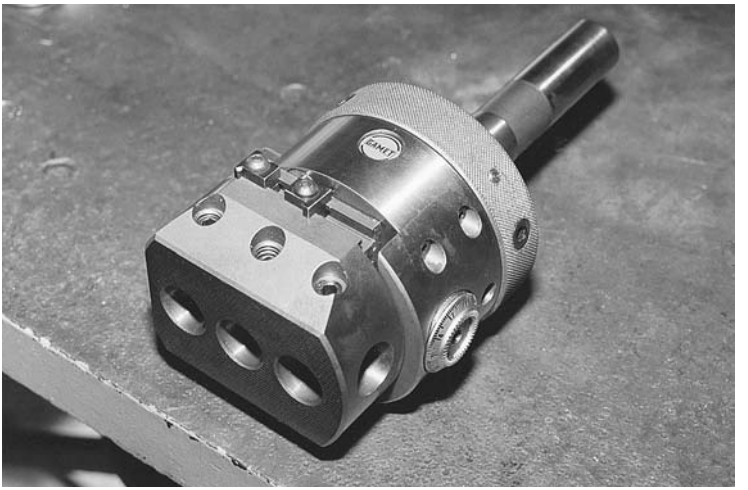

Figure 7.112 A modern removable-insert boring head.

the mechanical action of abrasive particles of irregular shape, size, and hardness. Grinding can be a rough or a precision operation for producing smooth surfaces, either flat, cylindrical, or irregularly shaped. The medium of the grinding operation is the grinding wheel, which is used for both external and internal grinding procedures. Grinding wheel shapes and other specifications are defined by the following ANSI standards:

ANSI B74.2-I982, Shapes and Sizes of Grinding Wheels

ANSI B74.3-I986, Shapes and Sizes of Diamond and Cubic Boron Nitride Abrasive Products

ANSI B74.I3-I990, Markings for Identifying Grinding Wheels and Other Bonded Abrasives

Other ANSI standards define chemical analysis, bulk density, size of abrasive grains, and other specifications for grinding products and testing procedures.

An ideal grinding abrasive has the ability to fracture before serious dulling occurs and offers maximum resistance to point wear. Each abrasive has a special crystal structure and fracture characteristics, making it suitable for grinding operations on specific materials.

Grinding wheels are composed of abrasive grains of preselected size bonded together with different bonding media. Five important

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considerations must be given to the selection of a grinding wheel to suit a particular application:

1. Abrasive type
2. Grain size
3. Bonding media
4. Grade or hardness of the wheel
5. Structure

Wheel abrasives

Natural abrasives. Corundum, emery, and diamond (corundum is natural aluminum oxide containing varying amounts of impurities).

Manufactured abrasives. Synthesized diamond, silicon carbide, aluminum oxide, and cubic boron nitride (CBN). These abrasives all have well-defined physical and chemical characteristics.

Grain size. Abrasive grains vary from 6 to 8 coarse grit to 1000 to 2000 grit for polishing and lapping.

Designation of grinding wheels. A standard marking system defined by ANSI 74.13-1990 for the identification of grinding wheels (excluding diamond and CBN) is shown in Fig. 7.113. From this marking system, you may determine the characteristics of the grinding wheel from its markings.

A standard marking system defined by ANSI B74.3-1986 for the identification of diamond and CBN is shown in Fig. 7.114. From this marking system, you may determine the characteristics of diamond and CBN grinding wheels.

Grinding wheel speeds. The most efficient operating speeds in surface feet per minute (sfpm) for general use are summarized in Fig. 7.115. The manufacturer of your particular wheel may recommend a different surface speed based on its experience with its product. Too low a speed will result in wasted abrasive and lower efficiency, and too high a speed may result in too hard grinding action and breakage of the grinding wheel. Do not exceed the maximum speed in revolutions per minute that is marked on each wheel. Severe injury can result from the flying fragments of a broken grinding wheel.

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Standard Bonded-Abrasive Wheel-Marking System - ANSI B74.13-1990

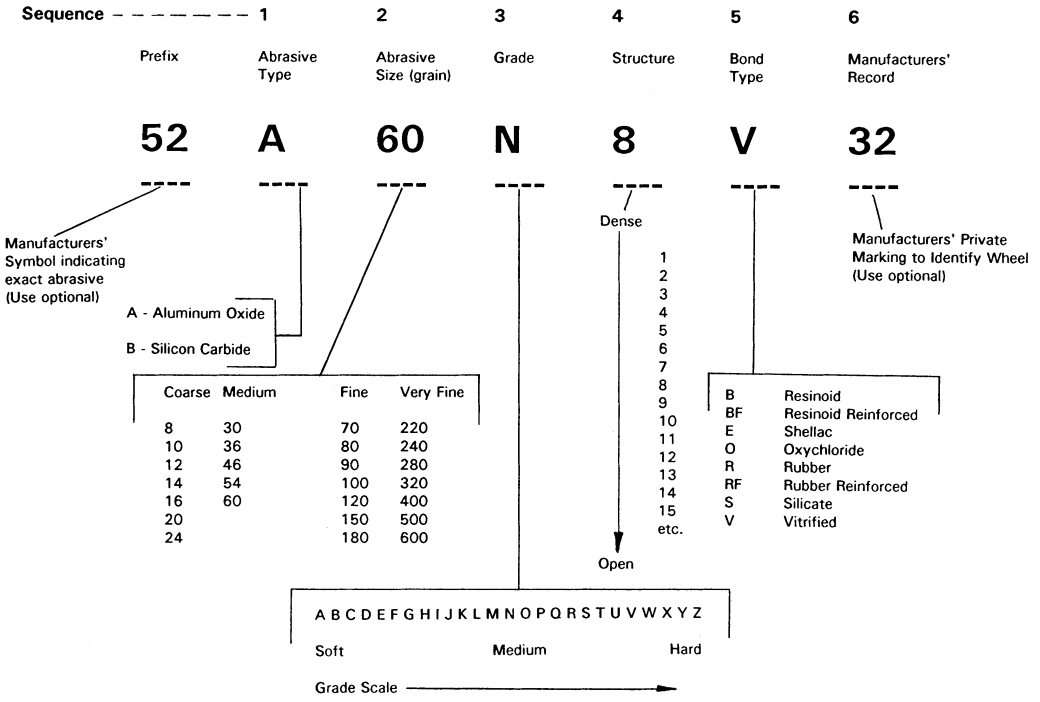

Figure 7.113 Grinding wheel marking system.

Standard Marking System for Diamond and Cubic Boron Nitride Grinding Wheels.
(ANSI B74.3-1986)

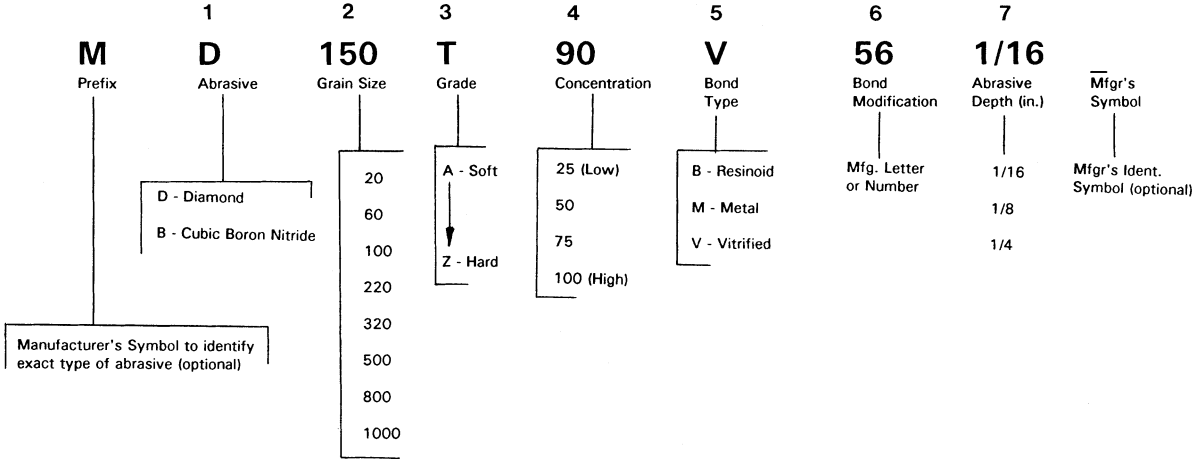

Figure 7.114 Marking system for diamond and CBN.

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Efficient Grinding Wheel Operating Speeds in Surface Feet Per Minute

Type of Operation	sfpm
Cutlery (large-offhand)	4,000-5,000
Cut-off (Rubber, shellac, resinoid)	9,000-16,000
Cylinders (Including hemming)	2,500-5,000
Cylindrical grinding	5,000-12,000
Disc grinding	4,000-5,500
Internal grinding	4,000-12,000
Knife grinding (machine knives)	3,500-4,500
Portable grinding	6,500-12,500
Snagging (vitrified small hole)	5,000-6,000
Snagging (resinoid and rubber)	7,000-9,500 - 12,500
Surface grinding	4,000-6,500
Tool grinding	5,000-6,000
Weld grinding	9,500-14,200

Note: The higher speeds are permitted only where bearings, protection devices and machine rigidity are adequate for the intended operation.
To convert sfpm to rpm use the following equation: rpm = (12 x sfpm)/(π x D)
Where: sfpm = surface feet per minute; π = 3.1416 and D = wheel diameter, inches.
CAUTION: Do not operate the grinding wheel above its marked maximum rpm limit.

Figure 7.115 Grinding wheel speeds.

Some of the standard shapes of grinding wheels are shown in Fig. 7.116. ANSI B74.2-1982 defines shapes and sizes, although different forms and shapes may be produced by some wheel manufacturers. Standard types and shapes of diamond or CBN grinding wheels are shown in Fig. 7.117. As can be seen from these figures, many shapes and sizes are available for a multitude of grinding operations, from roughing to tool and die finishes.

It is difficult in a modern machining and metalworking handbook to give the exact type or number of grinding wheel to use for any specific application because of the many variables that arise in actual production situations. The data given in this section are for reference and approximate applicational uses. The manufacturer of the grinding wheels and abrasives employed should be contacted for precise applications on any grinding operation.

Modern machine grinding equipment has been developed to a high degree over the past 40 years. Figure 7.118 shows a modern surface grinder used in tool and die making and other precision applications. In this machine, the grinding wheel is stationary, and the table traverses from left to right and reverses itself in a continuous travel until the final finish is produced on the workpiece. The grinding wheel moves vertically in exact increments to produce the required cut and surface finish. This type of machine is used for flat-surface grinding only.

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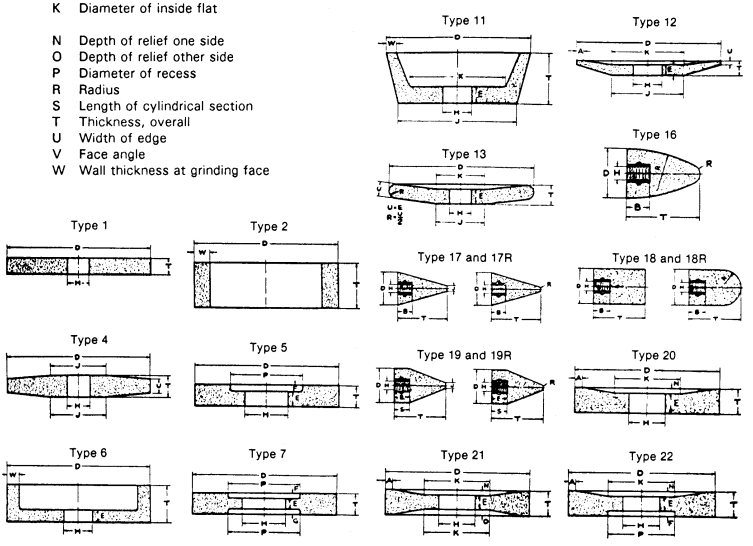

Figure 7.116 Standard grinding wheels.

Figure 7.119 shows a Brown and Sharpe cylindrical grinding machine in which the workpiece is rotated at the same time the grinding wheel is making the required surface finish on the cylindrical part.

The final quality or surface texture of machined and ground parts is usually given on the engineering drawing in root mean square (rms) numbers. An illustration of the finish texture according to the rms system is shown in Fig. 7.120. These finishes range from 500 to 2 rms, with the numbers representing microinches (μin) average. 500 rms would represent a roughing operation on a milling machine or shaper to a superfinishing operation of 2 μm, average or rms (root mean square). Finishes finer than 2 rms can

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Standard Types of Diamond or CBN Wheels - Norton Company (Abrasives Marketing Group) Worcester, Massachusetts

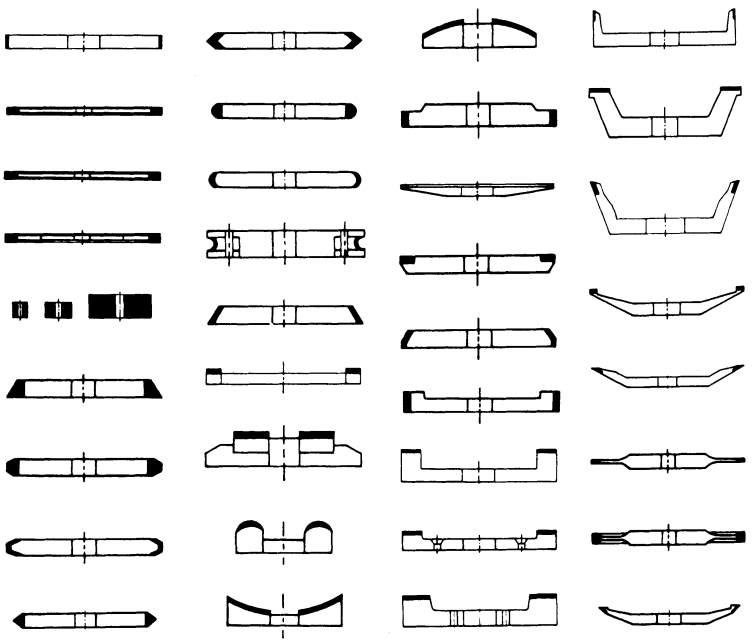

Figure 7.117 Diamond and CBN wheels.

be made using polishing compounds such as cerium oxide or rouge. Cerium oxide and rouge are used extensively in the optical industries for polishing lenses and reflecting mirrors. For finishes of higher rms values (ranging from 5 to 3 μin), compounds such as aluminum oxide powder may be used.

A convenient table of surface feet per minute converted to revolutions per minute of the grinding wheel is shown in Fig. 7.121. The figures in the table may be calculated using the following equation for converting surface feet per minute (sfpm) to revolutions per minute (rpm):

$$\text{sfpm} = \frac{\pi D(\text{rpm})}{12} \qquad \text{and} \qquad \text{rpm} = \frac{12(\text{sfpm})}{\pi D}$$

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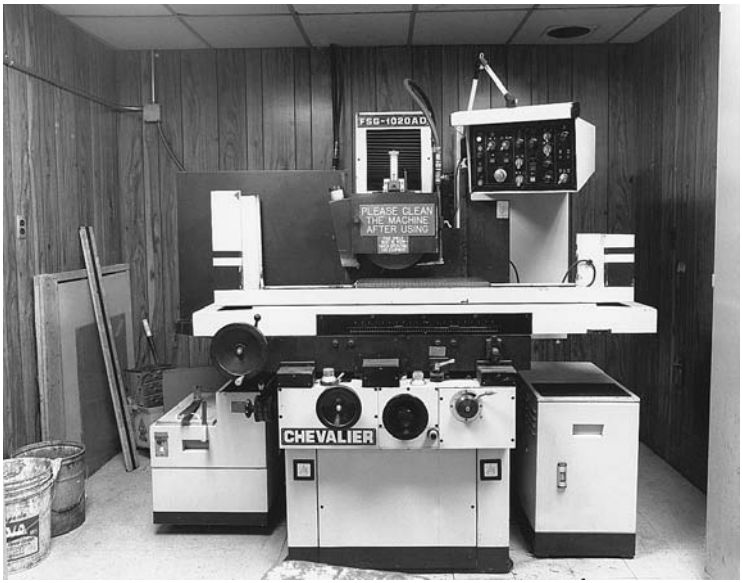

Figure 7.118 Modern automatic surface grinder.

Figure 7.119 Cylindrical grinding machine.

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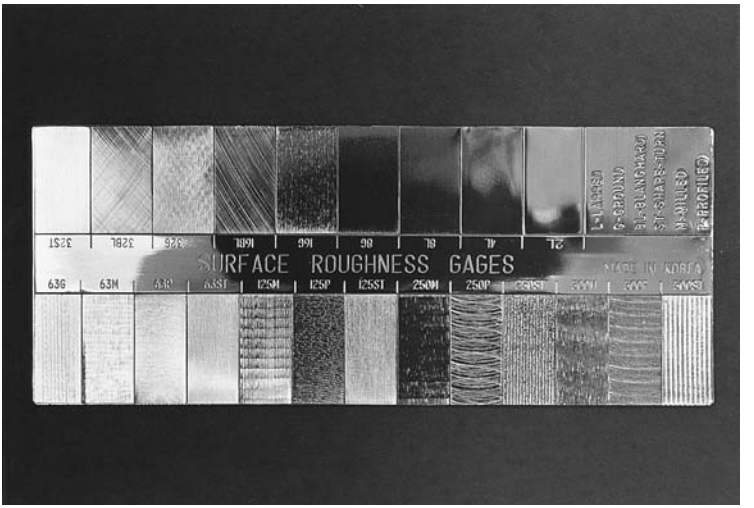

Figure 7.120 Surface roughness gauges.

Characteristics of grinding

Wheel speed. As wheel speed is increased, less work is required of each individual abrasive grain, and this promotes slower wheel wear.

Work speed. This is the speed at which the workpiece traverses the wheel or rotates about a center.

In-feed rate. The rate at which the wheel enters the workpiece during the grinding action. High in-feed rates increase wheel wear and produce a rougher finish than low in-feed rates.

Traverse or cross-feed. This is the rate at which the workpiece is moved across the face of the wheel. It is not the same as work speed.

Material to be ground. Materials to be ground are either metallic or nonmetallic, and the metallics are divided into low- or high-tensile types. Aluminum oxide wheels generally are used for grinding metallic materials, whereas diamond and CBN are used to grind the extremely hard metallics, as well as ceramics and other hard nonmetallics. Silicon carbide wheels generally are used to grind the

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Revolutions per Minute for Various Grinding Speeds in sfm - (Surface feet per minute)

Wheel Dia. Inches	4000	4500	5000	5500	6000	Periferal 6,500 Rev.	surface 7,000 per	speed 7,500 Minute	"sfm" 8,000 "rpm"	8500	9000	9500	10000	12000	14000	16000	Wheel Dia. Inches
1	15,279	17,189	19,099	21,008	22,918	24,828	26,738	28,648	30,558	32,468	34,377	36,287	38,197	45,837	53,476	61,115	1
2	7,639	8,594	9,549	10,504	11,459	12,414	13,369	14,324	15,279	16,234	17,189	18,144	19,099	22,918	26,738	30,558	2
3	5,093	5,730	6,366	7,003	7,639	8,276	8,913	9,549	10,186	10,823	11,459	12,096	12,732	15,279	17,825	20,372	3
4	3,820	4,297	4,775	5,252	5,730	6,207	6,685	7,162	7,639	8,117	8,594	9,072	9,549	11,459	13,369	15,279	4
5	3,056	3,438	3,820	4,202	4,584	4,966	5,348	5,730	6,112	6,494	6,875	7,257	7,639	9,167	10,695	12,223	5
6	2,546	2,865	3,183	3,501	3,820	4,138	4,456	4,775	5,093	5,411	5,730	6,048	6,366	7,639	8,913	10,186	6
7	2,183	2,456	2,728	3,001	3,274	3,547	3,820	4,093	4,365	4,638	4,911	5,184	5,457	6,548	7,639	8,731	7
8	1,910	2,149	2,387	2,626	2,865	3,104	3,342	3,581	3,820	4,058	4,297	4,536	4,775	5,730	6,685	7,639	8
9	1,698	1,910	2,122	2,334	2,546	2,759	2,971	3,183	3,395	3,608	3,820	4,032	4,244	5,093	5,942	6,791	9
10	1,528	1,719	1,910	2,101	2,292	2,483	2,674	2,865	3,056	3,247	3,438	3,629	3,820	4,584	5,348	6,112	10
12	1,273	1,432	1,592	1,751	1,910	2,069	2,228	2,387	2,546	2,706	2,865	3,024	3,183	3,820	4,456	5,093	12
14	1,091	1,228	1,364	1,501	1,637	1,773	1,910	2,046	2,183	2,319	2,456	2,592	2,728	3,274	3,820	4,365	14
16	955	1,074	1,194	1,313	1,432	1,552	1,671	1,790	1,910	2,029	2,149	2,268	2,387	2,865	3,342	3,820	16
18	849	955	1,061	1,167	1,273	1,379	1,485	1,592	1,698	1,804	1,910	2,016	2,122	2,546	2,971	3,395	18
20	764	859	955	1,050	1,146	1,241	1,337	1,432	1,528	1,6623	1,719	1,814	1,910	2,292	2,674	3,056	20
22	694	781	868	955	1,042	1,129	1,215	1,302	1,389	1,476	1,563	1,649	1,736	2,083	2,431	2,778	22
24	637	716	796	875	955	1,035	1,114	1,194	1,273	1,353	1,432	1,512	1,592	1.910	2,228	2,546	24
26	588	661	735	808	881	955	1,028	1.102	1,175	1,249	1,322	1,396	1,469	1,763	2,057	2,351	26
28	546	614	682	750	819	887	955	1,023	1,091	1,160	1,228	1,296	1,364	1,637	1,910	2,183	28
30	509	573	637	700	764	828	891	955	1.019	1,082	1.146	1,210	1,273	1,528	1,783	2,037	30
32	477	537	597	657	716	776	836	895	955	1,015	1,074	1,134	1,194	1,432	1,671	1,910	32
34	449	506	562	618	674	730	786	843	899	955	1,011	1,067	1,123	1,348	1,573	1,798	34
36	424	477	531	584	637	690	743	796	849	902	955	1,008	1,061	1,273	1,485	1,698	36
38	402	452	503	553	603	653	704	754	804	854	905	955	1,005	1,206	1,407	1,608	38

Figure 7.121 Rpm/surface-speed table.

softer-grade nonmetallics. Specific and specialized grinding applications should be referred to the grinding wheel manufacturer. Arbitrarily selecting a grinding wheel or relying on handbook listings of specific grinding wheels for exact operations may not be the best solution to your grinding requirements, especially as far as productivity and wheel wear are concerned.

Grinding wheel dressing. There are various forms of grinding wheel dressing tools available. Some of the many types of grinding wheel dressers include

- Helical hooded dressers
- Abrasive wheel dressers
- Single-stone diamond dressers
- Multiple-point diamond dressers
- T-type diamond hand dressers
- Diamond-stick dressers (silicon carbide)
- Dressing sticks for diamond and CBN grinding wheels
- Ball bearing dressers (for extremely accurate dressing)
- Diamond surface grinder wheel dressers (diamond nib)

7.7.2 Lapping

Lapping is a final finishing operation that results in four major improvements to a workpiece:

1. Extreme accuracy of dimension
2. Correction of minor imperfections
3. Better surface finish
4. Close fit between mating or faying surfaces

In normal lapping operations, less heat is generated than in most other finishing operations. In manual and semiautomatic machine lapping, the end results depend on the following major factors:

1. Type of lap material
2. Type of lapping medium or compound

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3. Speed of the lapping motion
4. The material to be lapped

Lap materials. Cast iron is the most efficient machine lapping material. Other materials used for hand lapping include soft steel, bronze, brass, lead, leather, and various cloths. Leather and cloth are used for polishing. The material of the lap should be softer than the material that is being lapped.

Lapping media

- Silicon carbide—for rapid stock removal
- Fused aluminum oxide—for soft steel and nonferrous alloys
- Unfused aluminum oxide—for excellent polishing action
- Diamond—for precious stones and tungsten carbides

The manufacturers who produce the lapping media also provide the proper mixtures and viscosities of the lapping solutions.

Lapping speeds. Efficient lapping speeds range from 300 to 8000 sfpm. Higher speeds will improve the surface finish. Lapping pressures range between 1 and 3 psi for soft materials and 10 psi for hard materials. In manual lapping, the final surface finish depends on the skill of the operator and the lapping medium. New materials that can be used for lapping include cerium oxide and microfine aluminum oxides of optical grade. There are no known materials other than optical rouge and cerium oxide for producing ultrafine finishes on glass and metallic materials.

7.7.3 Honing

Honing is a low-speed abrading process using bonded abrasive sticks for removing stock from metallic and nonmetallic materials. Honing corrects surface errors produced by other machining or grinding operations. Honing has its most important function in the final finishing of internal cylindrical surfaces.

Honing speeds. Figure 7.122 gives the approximate honing speeds for cast irons and steels, which are the most commonly honed materials. The combined rotation and reciprocation of a hone produces a cross-hatched surface finish on an internal cylindrical part.

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Honing Speeds - sfpm (surface feet per minute)

Material	Hardness R_C	Bore Character	sfpm
Steel	15-35	Interrupted	150
	15-35	Plain	80
	35-50	Interrupted	80
	35-50	Plain	60
	50-65	Interrupted	80
	50-65	Plain	50
Cast Irons	15-50	Interrupted	200
	15-50	Plain	110
	50-65	Interrupted	110
	50-65	Plain	60

Note:Tabular values are approximate and should be used as a guide.
Observe the honing action and take appropriate steps to refine the operation.

Figure 7.122 Honing speeds.

Honing abrasives. Honing sticks are produced with the following abrasives: silicon carbide, aluminum oxide, CBN, and diamond. Silicon carbide is used to hone cast irons and nonferrous materials, aluminum oxide is used to hone steels, and diamond and CBN are used on surfaces that have been chromium plated and other extremely hard materials.

Surfaces as fine as 3 to 4 μin are obtainable using 500 grit silicon carbide on steel parts. Grain sizes for manual and power stroke honing range from 150 to 1200 grit, according to the honing medium and the application.

7.7.4 Superfinishing

Using a bonded stick for cylindrical parts or a cup wheel for flat and spherical workpieces with an abrasive action, superfinishing may be performed. Superfinishing produces a highly wear-resistant finish on parts that are applicable for the superfinishing process. The objective in superfinishing is the removal of fragmentation or smear metal irregularities to restore surface geometry and the surface of the workpiece by eliminating surface stresses and burns. Stock removal may range from 0.0002 to 0.001 in. Scratch patterns of 30 μin rms or more to a mirror finish may be produced.

General-purpose and high-production superfinishing machines are available to produce a superfinish on almost any symmetric type of workpiece. The superfinishing stone is ground to the contour of the part to be superfinished, such as a cylindrical outside surface.

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Superfinishing is possible on the hardest of steels and other metallic alloys. Very fine mesh aluminum oxide is employed for many superfinishing applications.

Superfinishing speeds. The recommended speed for most superfinishing operations is from 50 to 60 sfpm at a pressure on the stone contact area of 10 to 35 psi. Superfinishing times are suprisingly fast, with steel of hardness Rockwell C 35 being finished from 20 to 1 μin in approximately 2 minutes under average pressure and with 500 mesh aluminum oxide as the abrasive medium. The use of optical-grade cerium oxide also may improve the finish after the aluminum oxide operation is completed.

7.8 Files and Sharpening Stones

7.8.1 Files

Common hand files generally are divided into three categories:

- American-pattern machinist's files
- Swiss-pattern files
- Special-purpose files

The correct selection and proper use of hand files require extensive experience to produce first-class results. The cutting efficiency of hand files is a function of tooth design, construction, material, and pattern of the teeth. Most files are made of high-carbon steel, heat treated to extreme hardness.

The standard files are either single-cut or double-cut, with some patterns being wavy or curved. Among the many types and designs of hand files, a new class of files has been introduced within recent years. These include the sintered-diamond Swiss-pattern files that contain diamond crystals on their surfaces of varying grades of fineness. These relatively new files will cut any material efficiently and are excellent for tool and die hand-working procedures on extremely hard steels.

Figure 7.123 shows the American-pattern standard machinist's files and their common uses and characteristics. Figure 7.124 shows the standard Swiss-pattern files with their characteristics and uses. Files are characterized by coarseness grade and type of cut.

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American Pattern Machinists' Files - Description and Uses

File Cross-Section	Name	Tooth Characteristic	General Uses
	Flat	Usually bastard cut. Also second- cut and smooth.	General purpose and lathe filing
	Hand	One edge smooth. Bastard, second-cut and smooth.	Finishing flat surfaces
	Pillar	One edge smooth. Bastard, second-cut and smooth	Keyways, slots and narrow work
	Warding	Usually bastard. also second-cut and smooth	Filing ward notches in keys and narrow work.
	Square	Bastard, second-cut and smooth.	Enlarging holes or recesses, mortises, keyways and splines.
	Three-Square	Sharp edges. Bastard, second-cut and smooth.	Filing acute angles, corners, grooves and notches.
	Round	Usually bastard. Also second-cut and smooth	Enlarging holes and shaping curved surfaces.
	Half-Round	Usually bastard. Also second-cut and smooth	Concave corners, crevices and round holes.
	Knife	Usually bastard. Also second-cut and smooth	Cleaning out acute angles, corners and slots.

Note: Many variations are available, including long angle lathe files, aluminum flat files, aluminum half-round files, regular taper saw files, chain saw files and cantsaw files.

Figure 7.123 Machinist's files.

Swiss Pattern Files - Description and Uses

File Cross-Section	Name	Tooth Characteristic	General Uses
	Hand	Double-cut on two flat faces and one edge. Other edge smooth.	Flat surfaces
	Pillar	Double-cut on two flat faces. Both edges smooth.	Flat surfaces and slots
	Warding	Double-cut on two flat faces. Single-cut on two edges.	Slots
	Square	Double-cut	Corners and holes.
	Three-Square	Double-cut three faces. Single-cut on edges	Corners and holes
	Round	Double-cut	Corners and holes
	Half-Round	Double-cut	Corners and holes
	Knife	Double-cut on flat faces. Single-cut on edges	Slots
	Crossing	Double-cut	Corners and holes
	Barrette	Cut on wide flat face. Other	Corners, flat surfaces, burring gear teeth.
	Crochet	Double-cut	Slots, flat surfaces and rounded corners.
	Cant	Double-cut three faces. Single cut on two sharp edges	Corners
	Pippin	Double-cut	Rounded corners and holes.

Figure 7.124 Swiss-pattern files.

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Coarseness grades

- Bastard cut—for heavy material removal with coarse finish
- Second cut—for light removal with fair finish
- Smooth cut—for fine finishing work

Cut types

- Single cut—used with light pressure for smooth finishes or to sharpen cutting surfaces
- Double cut—for use with heavier pressure to produce a rougher finish

Die sinker's files. These specialized files are used for dressing and finishing dies and are supplied in cut 0 and cut 2 with the same general types as Swiss-pattern files.

Die sinker's rifler files. These specialized files are used in die and mold work, instrument work, and other fine filing jobs. Figure 7.125 shows die sinker's rifler files with their associated trade number designations. These files are available in cut numbers 0, 2, and 4. Most Swiss-pattern and die sinker's files are available in various coarseness grades ranging from number 00 through 6. Number 00 is the coarsest and number 6 is the finest grade. Presently, these specialized files are produced with sintered-diamond and CBN surfaces for working the hardest steel dies and molds.

Figure 7.126 shows an assortment of Swiss-pattern files in 4-in length. The file at the top of the figure is a sintered-diamond equaling needle file. The diamond needle files come in the following shapes:

- Equaling, flat
- Half-round
- Three-square
- Round
- Knife

The diamond needle files have the following grades of coarseness:

- Fine—200/300 grit

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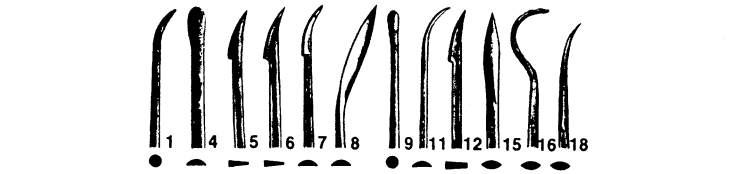

Figure 7.125 Die sinker's rifler files.

Figure 7.126 Swiss-pattern file samples, 4-in size (top is a diamond grit file).

- Medium—140/170 grit
- Coarse—100/120 grit

Rotary files and burrs. Rotary files and burrs are made from high-grade carbon steel as well as solid carbide. They are available in various shank diameters, including 3/32, 1/8, and 1/4 in. Rotary files and burrs are made in the following shapes: ball, cone, 60° cone, 90° cone,

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inverted cone, cylindrical flat end, cylindrical radius end, flame, oval, 14° taper radius end, tree-shape pointed end, and treeshape radius end. Both rotary files and burrs are made in single-cut and double-cut forms, with various degrees of coarseness.

7.8.2 Sharpening stones

Sharpening stones are made from the following abrasive types:

India stone (aluminum oxide). Used where close tolerances and smooth cutting edges are required.

Silicon carbide. Fastest cutting sharpening stone; used where speed is essential and moderate tolerances are permitted.

Arkansas. A natural stone recommended for final finishing that produces the highest precision edge possible.

Boron carbide. Next to diamond in hardness and will cut any material except diamond; used to dress carbide cutting tools.

Sharpening stones are made in file form also, with many different shapes available, such as those shown for the Swiss-pattern files in Fig. 7.124.

7.9 Knurling

Knurls are usually hob-cut to obtain sharp, perfectly formed teeth. Most knurls, either diamond or straight, are made from quality HSS (type M-4) or cobalt alloy (M-48). The knurls fit either revolving- or stationary-head knurling tools for use on lathe machines. The knurling tools are made in different sizes for use on lathes with swings of 7 through 36 in.

Standard-face diamond knurls are available in sizes ranging from 12, 16, 20, 24, 25, 30, 40, 50, to 80 teeth per inch. Standard straight knurls are available in sizes ranging from 12, 16, 20, 24, 25, 30, 40, 50, to 80 teeth per inch.

Straight knurling is a form of serrating. Both diamond and straight knurls are machined into a part either for gripping purposes, ornamental purposes, or both. Straight or diamond knurls are a necessity for parts such as thumb screws and the like, where the knurl provides a firm gripping surface. Knurl patterns are available in the following forms:

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- Straight
- 30° diagonal right-hand and left-hand (in sets to produce a diamond pattern)
- 30° diamond male
- 30° diamond female (indented knurl)
- Diametral pitch knurls

The knurl is machined into the part on the lathe as either a narrow band, where the knurling tool is in-fed into the workpiece, or as a continuous knurl, using the lathe carriage to automatically traverse the workpiece as in turning a screw thread.

7.10 JIC and ISO Carbide Codes

The Joint Industrial Council (JIC) carbide classification code system is shown in Fig. 7.127. Since this system evolved around the early cemented and sintered carbide grades, no provision was made for the newer, more advanced cutting tool materials. Also, the wide variety of cemented carbide compositions prevented the universal acceptance of a single classification system. Nevertheless, two grade-classification systems are presently accepted: the JIC system and the International Standards Organization (ISO) system. The ISO carbide grade-classification system is shown in Fig. 7.128.

Reference may be made to all the modern advanced cutting tool materials in Secs. 7.1, "Turning and Boring," and 7.2, "Milling." The Kennametal material tables also reference the JIC and ISO classifications for the cutting grades shown in the tables.

7.11 Cutting Fluids and Coolants for Machining Operations

Cutting fluids and machining coolants have been developed over the past 20 to 25 years that are very different from those used previously in industry. Many of the modern cutting fluids and coolants are designed and formulated to be environmentally safe and biodegradable. Some cutting fluids have been developed for use on specific types of materials, whereas others are suitable for a very wide range of different materials and cutting conditions. Some of

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JIC Carbide-Classification Code

Code	Application	Carbide Characteristics
C-1	Roughing	Medium-high shock resistance Medium-low wear resistance
C-2	General purpose	Medium shock resistance Medium wear resistance
C-3	Finishing	Medium-low shock resistance Medium-high wear resistance
C-4	Precision finishing	Low shock resistance High wear resistance
C-5	Roughing	High resistance to cutting temperatures Shock and cutting load Medium wear resistance
C-6	General purpose	Medium-high shock resistance Medium wear resistance Medium shock resistance
C-7	Finishing	Medium shock resistance Medium wear resistance
C-8	Precision finishing	Very high wear resistance Low shock resistance

Note: Hardness increases from top to bottom; toughness increases from bottom to top.

Figure 7.127 JIC carbide code.

the modern cutting fluids are supplied in aerosol cans and are sprayed on the workpiece while the machining operation is being performed. These spray-application fluids adhere strongly to the workpiece and allow easier machinability while preventing corrosion on the workpiece, such as rusting on ferrous materials.

Combination cutting fluids and coolants are being produced that may be used for most of the high-speed machining operations afforded by the advanced cutting tool materials. With the advent of universal-type cutting-coolant combination fluids, the inventory of cutting fluids and coolants can be kept to a minimum within a manufacturing facility or machine shop.

Modern coolants/cutting fluids. Cutting oils are divided into three basic types: petroleum oils, fixed (animal or vegetable) oils, and synthetic oils. Chemical additives give oils additional or enhanced properties such as resistance to oxidation and foaming and the ability to perform under extreme pressures and temperatures.

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ISO Carbide Classification System - International Standards Organization

Main Machining Group	Color Marking	Application Group	Operations and Working conditions
P Group: steel cast steel, long chip malleables	Blue	P01	High precision turning and boring. High cutting speeds. Good surface finish and vibration-free machining
		P10	Turning, thread cutting and milling. High cutting speeds. Small/medium chip cross-section
		P20	Turning, milling, medium cutting speeds and medium chip cross-section. Planing - small chip.
		P30	Turning, milling, planing. Medium to low cutting speeds. Medium/large chip cross-section. Unfavorable conditions
		P40	Planing, turning, milling, shaping. Low cutting speeds. Large chip cross-section. High rake angles. Unfavorable conditions
		P50	Where highest demands are made on carbide toughness. Turning, planing and shaping. Low cutting speeds. Large chips and high rakes. Unfavorable conditions.
M Group: steel, cast steel austenitic manganese steels, cast iron alloys, austenitic steels, malleable cast iron, free-cutting steels.	Yellow	M10	Turning. Medium-high cutting speeds. Small to medium chip cross-section.
		M20	Turning, milling. Medium cutting speeds and medium chip cross-section.
		M30	Turning, milling, planing. Medium cutting speeds. Medium/large chip cross-section.
		M40	Turning, form turning, parting off and recessing - for automatics.
K Group: cast iron, chilled cast irons, short chip malleables hardened steels, nonferrous metals and nonmetallic materials.	Red	K01	Turning, precision turning/boring. Finish milling and scraping.
		K10	Turning, milling, boring, countersinking. reaming, scraping and broaching.
		K20	Turning, milling, planing, countersinking. scraping, reaming and broaching under tougher conditions than K10.
		K30	Turning, milling, planing, shaping under unfavorable conditions. High rakes.
		K40	Turning, milling, planing, shaping under unfavorable conditions. High rakes.

Note: Cutting speed and wear resistance increase from bottom to top; feed and carbide toughness increase from top to bottom.

Figure 7.128 ISO carbide classification system.

Some of the modern coolants/cutting fluids and compounds include

Nonhazardous cutting compounds. Biodegradable, contain no 1,1,1-trichloroethane.

Plumber's lard oil. Used for mixing with mineral oils.

Wax cut cutting oil. Chlorinated waxes suspended in clear oil.

Medium-duty soluble oil. Used where tool life and surface finish are critical.

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Thred Kut. Heavy-duty brown sulfochlorinated cutting oil, antiweld, antiwear solution.

Sulfur-base cutting oils. Used for all metals and high-alloy steels.

Kleen Kut soluble oil. Water-soluble emulsion; economical; mixed with water at 5% to 10% concentration.

Thred Kut 99. A dark, heavy sulfochlorinated fatty oil for machining and grinding soft, tough, and stringy metals such as stainless steels, low-carbon steels, jet-engine alloys, and monel metals.

Trampol-X cutting fluid. Economical, water-soluble, and efficient cutting fluid/coolant for all types of machining operations; designed to withstand recycling in central coolant systems.

Synthetic coolant. Heavy-duty synthetic cutting and grinding concentrate for machining ferrous alloys, aluminum, and brasses.

Blasocut. A high-efficiency cutting-coolant fluid for all types of machining operations; used in central coolant systems and fed at high pressures into the tool and workpiece cutting area; water-soluble; made in Switzerland; frequently used on turning center and machining center CNC machines.

7.12 Calculations for Common Machining Problems

7.12.1 Drill point advance

When drilling a hole, it is often useful to know the distance from the cylindrical end of the drilled hole to the point of the drill for any angle point and any diameter drill. Refer to Fig. 7.129, where the advance t is calculated from

$$\tan\left(\frac{180-\alpha}{2}\right)=\frac{t}{D/2}$$

Then

$$t=\frac{D}{2}\tan\left(\frac{180-\alpha}{2}\right)$$

where D = diameter of drill, in
α = drill point angle

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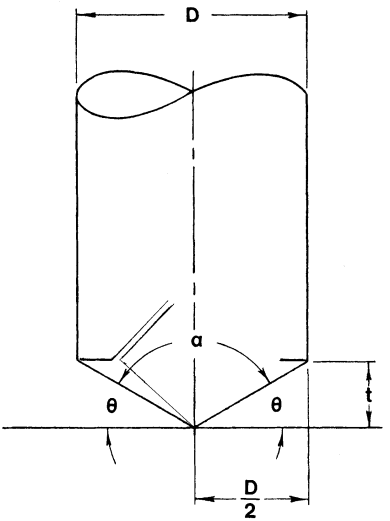

Figure 7.129 Drill advance.

Example: What is the advance t for a 0.875-in-diameter drill with a 118° point angle?

$$t = \frac{0.875}{2} \tan\left(\frac{180 - 18}{2}\right) = 0.2629 \text{ in}$$

$$\textit{Note}: \left(\frac{180 - \alpha}{2}\right) = \text{angle } \theta \text{ (reference)}$$

7.12.2 Tapers

Finding taper angles under a variety of given conditions is an essential part of machining mathematics. Following are a variety of taper problems with their associated equations and solutions.

For taper in inches per foot, see Fig. 7.130*a*. If the taper in inches per foot is denoted by T, then

$$T = \frac{12(D_1 - D_2)}{L}$$

where D_1 = diameter of larger end, in
D_2 = diameter of smaller end, in
L = length of tapered part along axis, in
T = taper, in/ft

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Also, to find the angle θ, use the relationship

$$\tan\theta = \frac{12 - (D_1 - D_2)}{L}$$

and then find arctan θ for angle θ.

Example: $D_1 = 1.255$ in, $D_2 = 0.875$ in, and $L = 3.5$ in. Find angle θ.

$$\tan\theta = \frac{1.255 - 0.875}{3.5} = 0.43429$$

$$\arctan 0.43429 = 23.475^\circ$$

Figure 7.130*b* shows a taper angle of 27.5° in 1 in, and the taper per inch is therefore 0.4894. This is found simply by solving the triangle formed by the axis line, which is 1 in long, and half the taper angle,

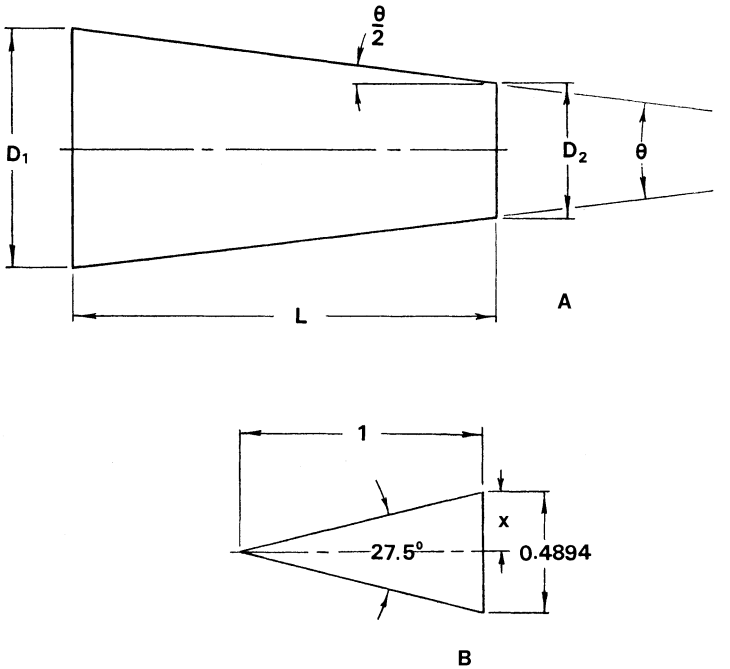

Figure 7.130 Taper angles.

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which is 13.75°. Solve one of the right-angled triangles formed by the tangent function:

$$\tan 13.75° = x/1$$

and

$$x = \tan 13.75° = 0.2447$$

and

$$2 \times 0.2447 = 0.4894$$

as shown in Figure 7.130*b*. The taper in inches per foot is equal to 12 times the taper in inches per inch. Thus, in Fig. 7.130*b*, the taper per foot is $12 \times 0.4894 = 5.8728$ in.

7.12.3 Typical taper problems

1. Set two disks of known diameter and a required taper angle at the correct center distance L (see Fig. 7.131).
   Given: Two disks of known diameter d and D and the required angle θ. Solve for L.

$$L = \frac{D - d}{2\left(\sin\frac{\theta}{2}\right)}$$

2. Find the angle of the taper when given the taper per foot (see Fig. 7.132).
   Given: Taper per foot T. Solve for angle θ.

$$\theta = 2\left(\arctan\frac{T}{24}\right)$$

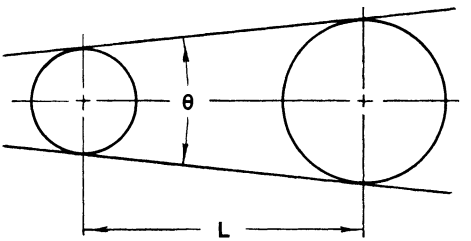

Figure 7.131 Taper.

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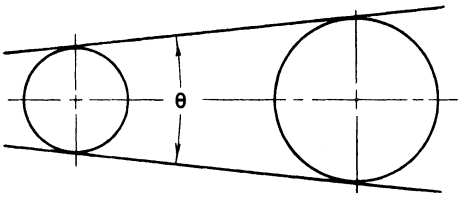

Figure 7.132 Angle of taper.

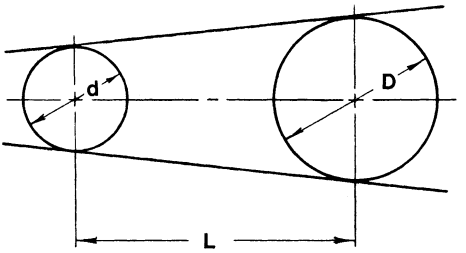

Figure 7.133 Taper per foot.

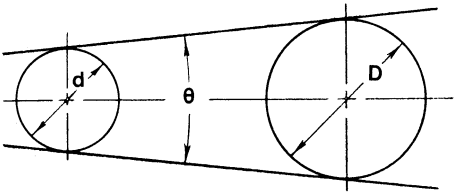

Figure 7.134 Angle of taper.

3. Find the taper per foot when the diameters of the disks and the length between them are known (see Fig. 7.133).
   Given: d, D, and L. Solve for T.

$$T = \tan\left(\arcsin\frac{D-d}{L}\right) \times 24$$

4. Find the angle of the taper when the disk dimensions and their center distance are known (see Fig. 7.134).
   Given: d, D, and L. Solve for angle θ.

$$\theta = 2\left(\arcsin\frac{D-d}{2L}\right)$$

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5. Find the taper in inches per foot measured at right angles to one side when the disk diameters and their center distance are known (see Fig. 7.135).
   Given: d, D, and L. Solve for T, in inches per foot.

$$T = \tan\left[2\left(\arcsin\frac{D-d}{2\left(\sin\frac{\theta}{2}\right)}\right)\right]\times 12$$

6. Set a given angle with two disks in contact when the diameter of the smaller disk is known (see Fig. 7.136).
   Given: d and θ. Solve for D, diameter of the larger disk.

$$D = \left(\frac{2d\sin\frac{\theta}{2}}{1-\sin\frac{\theta}{2}}\right)+d$$

Figure 7.137 shows an angle-setting template that may be constructed easily in any machine shop. Angles of extreme precision are possible to set using this type of tool. The diameters of the disks may be machined precisely, and the center distances between the disks may be set with a gauge or Jo-blocks. Also, any angle may be repeated when a record is kept of the disk diameters and the precise

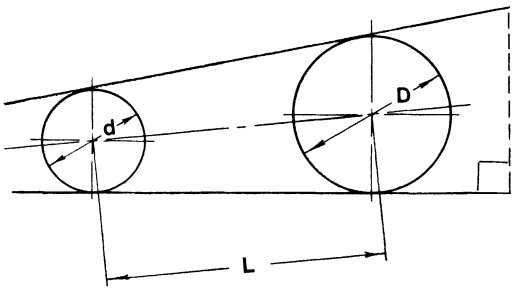

Figure 7.135 Taper in inches per foot.

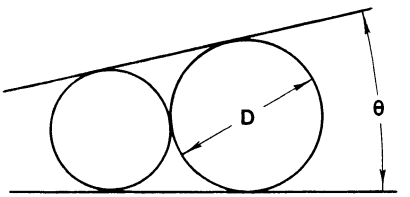

Figure 7.136 Setting a given angle.

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center distance. The angle θ, taper per inch or taper per foot, may be calculated using some of the preceding equations.

7.12.4 Checking angles and notches with plugs

A machined plug may be used to check the correct width of an angular opening or machined notch or to check templates or parts that have corners cut off or in which the body is notched with a right angle. This is done using the following techniques and simple equations.

In Figs. 7.138 through 7.140, $D = a + b - c$ (right-angle notches). To check the width of a notched opening, see Fig. 7.141 and the following equation:

$$D = W \tan\left(45° - \frac{\theta}{2}\right)$$

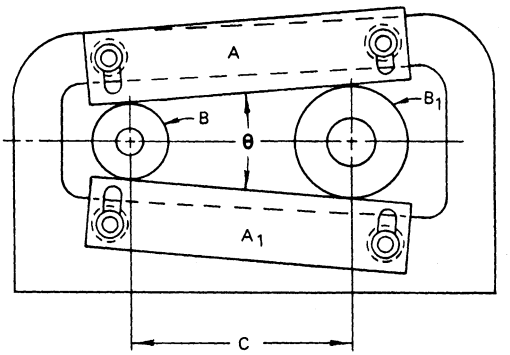

Figure 7.137 Angle-setting template.

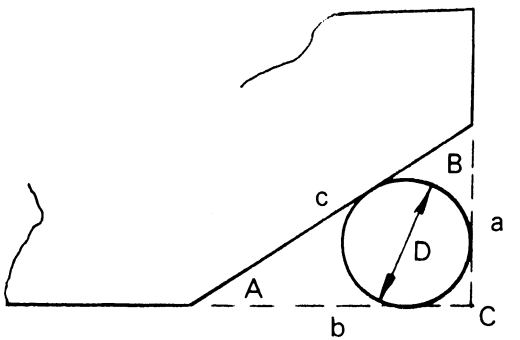

Figure 7.138 Right-angle notch.

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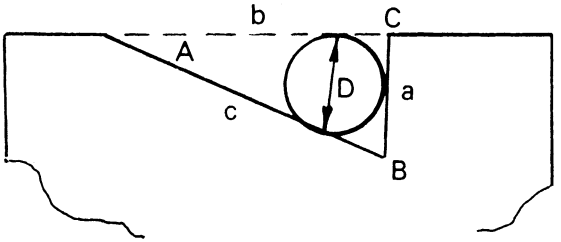

Figure 7.139 Right-angle notch.

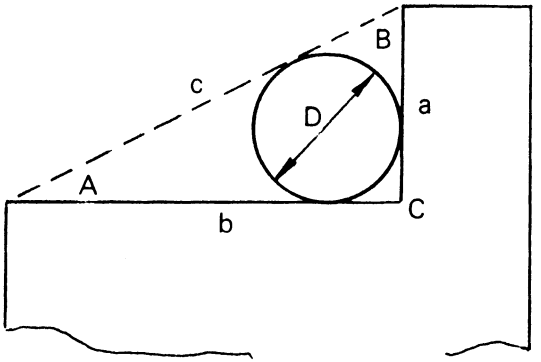

Figure 7.140 Right-angle notch.

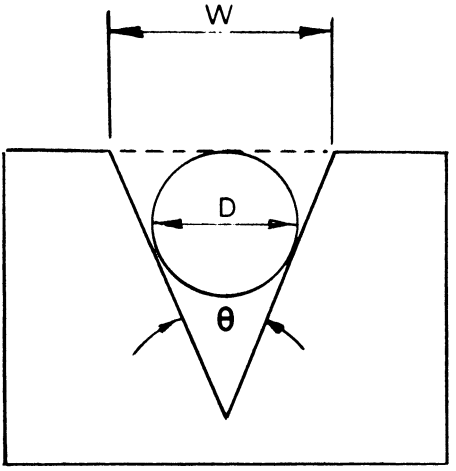

Figure 7.141 Width of notched opening.

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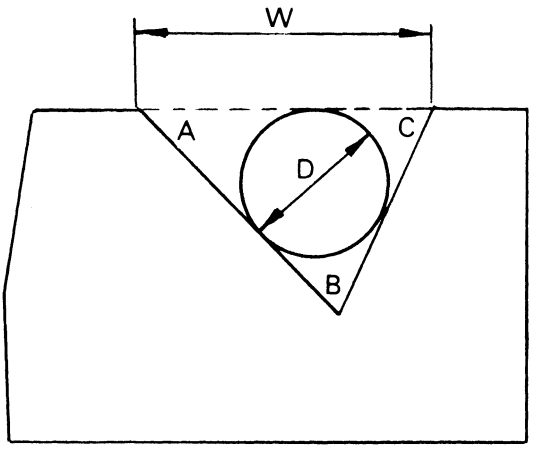

Figure 7.142 Finding plug diameter.

When the correct size plug is inserted into the notch, it should be tangent to the opening indicated by the dashed line.

Also, the equation for finding the correct plug diameter that will contact all sides of an oblique or non-right-angle triangular notch is as follows (see Fig. 7.142):

$$D = \frac{2W}{\left(\cot\frac{A}{2}\right) + \left(\cot\frac{B}{2}\right)}$$

where W = width of notch, in
A = angle A
B = angle B

7.12.5 Finding diameters

When the diameter of a part is too large to measure accurately with a micrometer or vernier caliper, you may use a 90° or any convenient included angle on the tool (which determines angle A) and measure the height H as shown in Fig. 7.143. The simple equation for calculating the diameter D for any angle A is as follows:

$$D = H\frac{2}{\csc A - 1}$$

Note: Cosecant 45° = 1.4142.

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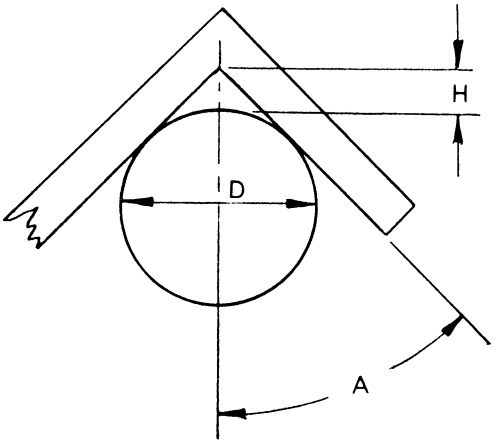

Figure 7.143 Finding the diameter.

Thus the equation for measuring the diameter D with a 90° square reduces to

$$D = 4.828H$$

Then, if the height H measured was 2.655 in, the diameter of the part would be

$$D = 4.828 \times 2.655 = 12.818 \text{ in}$$

When measuring large gears, a more convenient angle for the measuring tool would be 60°, as shown in Fig. 7.144. In this case, the calculation becomes simple. When the measuring angle of the tool is 60° (angle A = 30°), the diameter D of the part is $2H$.

For measuring either inside or outside radii on any type of part such as a casting or a broken segment of a wheel, the calculation for the radius of the part is as follows (see Figs. 7.145 and 7.146):

$$r = \frac{4b^2 + c^2}{8b}$$

where r = radius of part, in
b = chordal height, in
c = chord length, in

The chord should be made from a precisely measured piece of tool steel flat, and the chordal height b may be measured with an inside telescoping gauge or micrometer.

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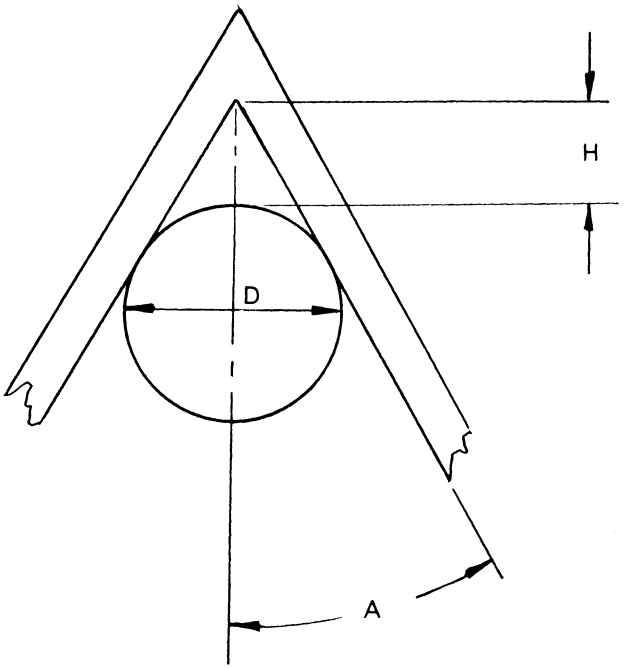

Figure 7.144 Finding the diameter.

7.12.6 Measuring radius of arc by measuring over rolls or plugs

Another accurate method of finding or checking the radius on a part is illustrated in Figs. 7.147 and 7.148. In this method, we may calculate either an inside or an outside radius by the following equations:

$$r = \frac{(L+D)^2}{8D} \qquad \text{for convex radii (Fig. 7.147)}$$

$$r = \frac{(L+D)^2}{8(h-D)} + \frac{h}{2} \qquad \text{for concave radii (Fig. 7.148)}$$

where L = length over rolls or plugs, in
D = diameter of rolls or plugs, in
h = height of concave high point above the rolls or plugs, in

For accuracy, the rolls or plugs must be placed on a tool plate or plane table and the distance L across the rolls measured accurately.

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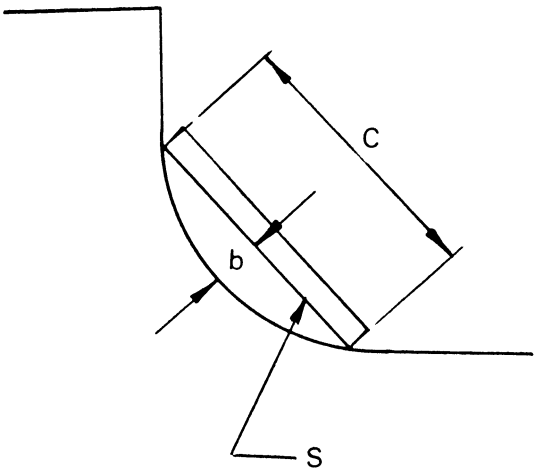

Figure 7.145 Finding the radius.

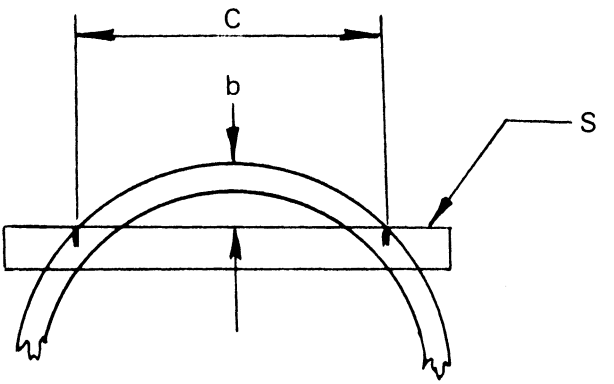

Figure 7.146 Finding the radius.

The diameter D of the rolls or plugs also must be measured precisely and the height h measured with a telescoping gauge or inside micrometers.

7.12.7 Measuring dovetail slides

The accuracy of machining of dovetail slides and their given widths may be checked using cylindrical rolls (such as a drill rod) or wires and the following equations (see Fig. 7.149):

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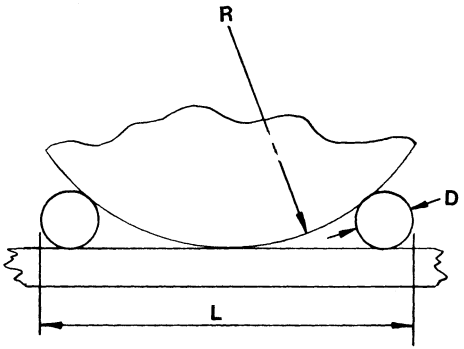

Figure 7.147 Finding the radius.

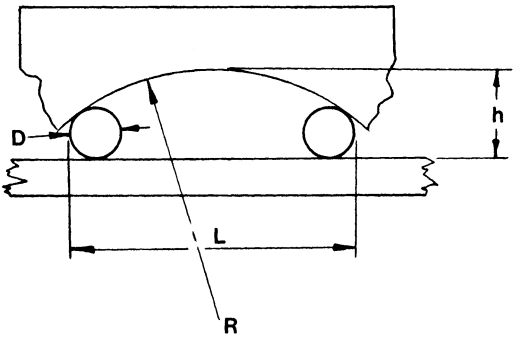

Figure 7.148 Finding the radius.

$$x = D\left(\cot\frac{\theta}{2}\right) + \alpha \qquad \text{for male dovetails (Fig. 7.149}a\text{)}$$

$$y = b - D\left(1 + \cot\frac{\theta}{2}\right) \qquad \text{for female dovetails (Fig. 7.149}b\text{)}$$

Note: $c = h \cot \theta$. Also, the diameter of the rolls or wire should be sized so that the point of contact θ is below the corner or edge of the dovetail.

7.12.8 Universal dividing heads

The precision universal dividing head is a precision milling attachment used to divide the circumference of circular work and to equally

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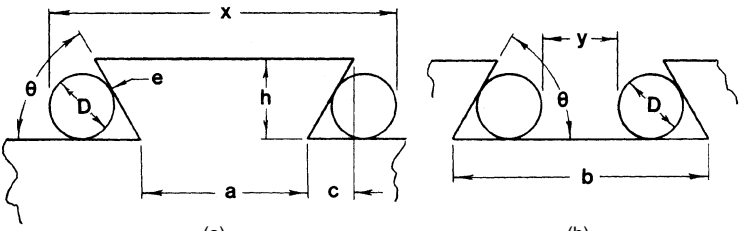

Figure 7.149 Measuring dovetail slides.

space the divisions. This milling tool may be used for milling spur gear teeth (using the appropriate cutter), pinion gears, splines, and spacing holes on a given circle. Other types of milled parts that may be produced using the universal dividing head include hexagonal nuts, octagons, pentagons, and other polygon shapes.

Refer to Fig. 7.150, in which *A* denotes the dividing head, *B* the indexing plates, and *C* the tail stock center. Work may be mounted between the head and tail stock centers or held in a chuck or collet, either of which is placed on the head spindle. Rotating the head crank causes the head stock spindle to rotate at a ratio of 40:1. This ratio and an index plate with a series of equally spaced holes (to measure and stop the crank rotation) make it possible to divide the circumference of the workpiece into the required number of equal divisions or sections.

The index plates (*B*) have different hole series, such as 15, 16, 17, 18, 19, 20, 21, 23, 27, 29, 31, 33, 37, 39, 41, 43, 47, and 49. An index chart of all possible divisions is supplied with the universal dividing head. These dividing heads usually are supplied in either left-hand or right-hand models, according to your particular setup and requirements. The precision dividing head usually can hold the angular divisions to within 10 seconds of arc.

Some dividing-head models are equipped with index plates and a series of change gears to alter the ratio of divisions. Instructions for the use of each particular dividing head must be obtained from the manufacturer. A precision dividing head is a necessary machine tool accessory in any model shop, machine shop, or tool and die operation that requires precise division of a circle.

7.13 Taps and Dies for Threading Operations

The tapping of threaded holes and the die cutting of external threads with the use of taps and dies are performed most efficiently and eco-

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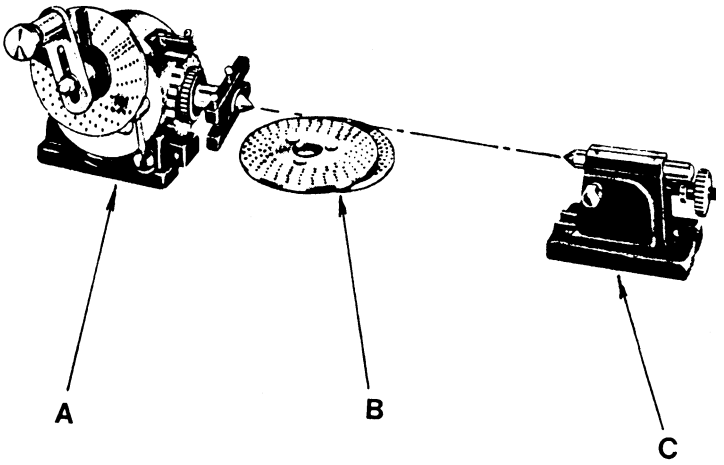

Figure 7.150 Universal dividing head.

nomically when the correct type of tap or die is used. The number of flutes on the tap and the style of flutes are important in the efficient removal of material that is cut in the tapping process. Four flute taps dispose of the cut material in shallow or large-diameter holes or when the material breaks into small chips but are not efficient in cutting stringy materials for deep or small-diameter holes.

Taps are available in spiral-point form, which allows the tap to push the cut material ahead of the tap on through holes. Spiral-flute and high-spiral-flute designs are made to pull the cut material up and out of the tapped hole during the tapping procedure. Thread-forming taps are also available that do not produce chips because the forming of the thread is a metal deforming or displacement process.

Some of the typical standard types of taps and dies are shown in Fig. 7.151. To produce a full thread to the bottom of a drilled hole, a standard set of taps is used, which includes the taper tap, plug tap, and bottoming tap used in the order listed to produce a fully threaded blind hole.

7.13.1 Available types of taps and dies

Taps

- Two-flute taps
- Three-flute taps
- Four-flute taps

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- Cut-thread taps
- Ground taps
- 30° spiral-flute taps
- 52° spiral-flute taps
- Spiral-point taps
- Straight and tapered pipe taps
- Interrupted-thread taps
- Pulley taps
- Nut taps
- Combined tap and drill

Dies

- Round adjustable dies
- Thread-cone dies (acorn type)
- Hexagon rethreading dies (standard thread and pipe thread)
- Square bolt dies
- Square pipe dies
- Locknut-thread round adjustable dies

Taps and dies are made from carbon steel, HSS, and solid carbide (plain or titanium nitride coated). Taps and dies are made for American standard unified threads, ISO metric threads, Acme threads, BA (British Association) threads, and other special thread forms used in industry. Most taps and dies are available in either right-hand or left-hand thread.

Although taps are produced in both cut-thread and ground-thread forms, the ground-thread tap is preferred for the following reasons:

1. The ground-thread tap will produce more than five times the number of holes than will the cut tap.
2. Although the ground-thread tap is more costly, it is more economical owing to its long wear ability.
3. A ground tap will produce a more accurate tapped hole.
4. It requires less machine power to use the ground tap on a size-to-size basis.

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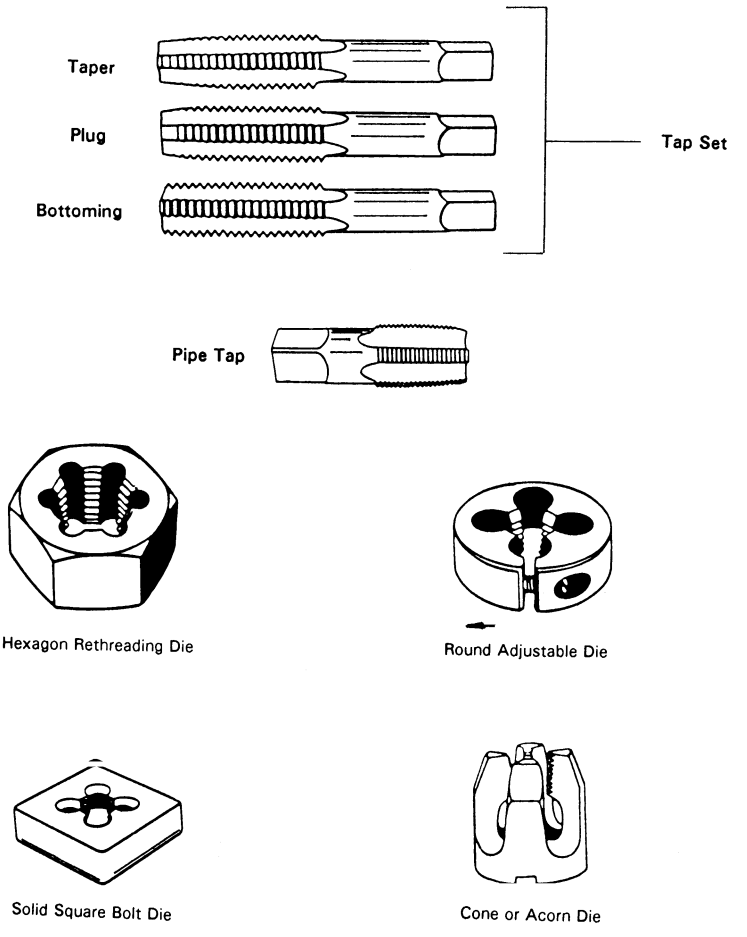

Figure 7.151 Typical standard taps and dies.

5. The cut-thread tap is usually not suitable for producing class 3B tapped holes.

The application of the proper cutting fluid is critical to economical and successful tapping operations. Various modern types of cutting fluids are produced for tapping and die-cutting threads on different materials. It is essential to use the proper type of cutting fluid for each specific type of tapping and die-cutting operation. The proper cutting fluids and cutting fluid direction and pressure are important

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on high-speed tapping operations, such as those performed on CNC turning centers and machining centers.

7.13.2 Speeds for tapping

The normal tapping speed for any particular material when using an HSS ground-thread or carbide tap should be the same as the drilling speed for the equivalent drill diameter. See Sec. 7.3 for the cutting speeds and revolutions per minute required for different materials and drill diameters to arrive at the required tapping speed or revolutions per minute.

7.13.3 Thread lead tolerances

Ground-thread taps always should be used when a threaded assembly must carry a heavy load. The thread lead tolerance on cut-thread taps is much broader than the close-tolerance thread lead produced by the ground-thread tap and will cause the threads to not maintain a full thread-bearing condition, which is detrimental to the strength of the tapped and threaded assembly. In other words, if the thread leads of the male thread do not coincide closely with the thread leads of the nut or tapped hole, a weak threaded assembly results or may not assemble easily.

The thread lead tolerances of cut-thread and ground-thread taps is as follows:

- Cut-thread tap lead tolerance = ±0.0030 in/in.
- Ground-thread tap lead tolerance = ±0.0005 in/in.

Pitch-diameter tolerance ranges of cut-thread and ground thread taps are as follows (actual tolerance depends on the thread size):

- Cut-thread pitch-diameter tolerance range = 0.001 to 0.0055 in/in.
- Ground-thread pitch-diameter tolerance range = 0.0005 to 0.0025 in/in.

7.13.4 Limit numbers for ground-thread taps (American UN thread system, ANSI)

All American standard listed ground-thread taps are marked with the capital letter G to designate ground thread. The letter G is followed by either the letter H or the letter L. The letter H designates

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above the basic pitch-diameter limits, and the letter L designates below the basic pitch-diameter limits. The number following the letter H or L designates the pitch-diameter limits. The number is a code number that references the actual dimensional limits of the basic pitch diameter. Figure 7.152 shows the H or L code number with the associated pitch-diameter limit dimensions.

Example: A tap marked GH2 indicates a ground-thread tap with pitch diameter limits of 0.0005 to 0.0010 in over the basic pitch diameter on sizes 1 in and under.

Note: Do not confuse these limit codes with the class of fit for a particular thread size. These tap-limit numbers are not related to the class of fit.

7.13.5 Limit numbers for ground-thread ISO metric taps

When the tap basic pitch diameter is over the basic thread pitch diameter by even multiples of 0.0005 in, the tap will be marked with the letter D. When the tap basic pitch diameter is under the basic thread pitch diameter by even multiples of 0.0005 in, the tap will be marked with the letters DU. The letters D and DU are followed by the limit number, which is determined as follows:

The D limit number. Amount the tap pitch diameter high limit is over basic pitch diameter, divided by 0.0005 in.

Limit Number Codes for Ground-Thread Taps - Pitch Diameter Limits

Limit Number Code	Pitch Diameter Limits	Tap Size
L1	Basic to basic minus 0.0005"	All to 1" diameter
H1	Basic to basic plus 0.0005"	"
H2	Basic plus 0.0005" to 0.001"	"
H3	Basic plus 0.001" to 0.0015"	"
H4	Basic plus 0.0015" to 0.002"	"
H5	Basic plus 0.002" to 0.0025"	"
H6	Basic plus 0.0025" to 0.003"	"
H7	Basic plus 0.003" to 0.0035"	"
H4	Basic plus 0.001" to 0.002"	Over 1" to 1.500" diameter

Note: The limit code number divided by 2 equals in thousandths of an inch, the amount that the maximum tap pitch diameter is above basic in the H series and the amount that the minimum tap pitch diameter is under basic in the L series.

Figure 7.152 Limit number codes for ground-thread taps.

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The DU limit number. Amount the tap pitch diameter low limit is under basic pitch diameter, divided by 0.0005 in.

Examples: M12 × 1.75, marked D6 limit: The maximum tap pitch diameter equals basic pitch diameter plus 0.0030 in (6 × 0.0005 = 0.0030 in). Tap pitch-diameter tolerance is minus 0.0012 in.

M6 × 1, marked DU4 limit: The minimum tap pitch diameter equals basic pitch diameter minus 0.0020 in (4 × 0.0005 = 0.0020 in). Tap pitch-diameter tolerance is plus 0.0010 in.

Note: See ANSI/ASME Standard B94.9-1987, *Taps, Cut and Ground Threads.*

Tap markings. All taps are marked with the nominal thread size, number of threads per inch, and a symbol to identify the thread form. On multiple-thread lead taps, the lead is marked in fractions and type of lead, such as double, triple, etc. Also, the hand of the thread is marked on the tap, i.e., LH for left hand and RH for right hand.

Example: A ¼-20 unified national coarse double-lead left-hand tap would be marked

¼-20UNC Double LH 1/10 in lead

See Chap. 14, "Fastening and Joining Techniques and Hardware."

7.13.6 Thread gauges (external and internal)

As shown in the preceding section on taps and dies, taps are made with ground thread forms that have pitch-diameter limits. Note also that the round adjustable dies for cutting external threads may be set with their set screw to cut the thread larger by a few thousandths of an inch. With these capabilities on the taps and dies, any particular class of fit for a particular thread size and pitch may be produced (i.e., 1, 2, 3, 1A, 2A, 3A, 1B, 2B, and 3B). Classes 1, 1A, and 1B are loose-tolerance threads; 2, 2A, and 2B are moderate- or common-tolerance threads; and 3, 3A, and 3B are close-tolerance thread fits.

In all production applications of thread cutting such as tapped holes, threaded rods, or hardware such as bolts, screws, and nuts, a method for controlling the class of fit must be employed. To accomplish this, inspection procedures using thread gauges are employed.

Some of the gauges used for the quality-control inspection of threaded parts include

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- Work-plug gauges—thread-setting plugs [American (inch) and metric]
- Thread-ring gauges [American (inch) and metric]
- Working thread-plug gauges [American (inch) and metric]

Note: Thread-setting plugs are used to check the ring gauges for wear.

7.14 Drill-Rod Types and Sizes for Machining and Tooling Applications

7.14.1 U.S. Customary or inch-size drill rods

U.S. Customary or inch-system drill rods generally are supplied in 36-in lengths in the following grades of material:

0-1. Oil-hardening for general toolroom use; good nondeforming characteristics; moderate resistance to abrasion; machinability 90 percent.

S-7. Air-hardening molybdenum, chromium; shock resisting; high impact strength with moderate wear resistance; machinability 95 percent.

A-2. Air-hardening; maximum abrasion resistance; machinability 65 percent.

D-2. Air-hardening; high carbon, high chrome; high wear resistance; machinability 50 percent.

W-1. Water-hardening offers a combination of high abrasion resistance and toughness; machinability 100 percent.

The five grades listed may be heat-treated and drawn or tempered to various hardness classes by using the heat-treating data shown in Chap. 11.

Available diameters. U.S. Customary drill rods are available in the following diameters (inches): 0.0625, 0.1250, 0.1875, 0.2500, 0.3125, 0.3750, 0.4375, 0.5000, 0.5625, 0.6250, 0.7500, 0.8750, 1.000, 1.1250, 1.2500, and 1.5000. Other diameters are also available. W-1 is the most economical, and D-2 is the most expensive, with the other grades falling between these two limits.

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Tolerances on drill rod

Up to 0.125 in in diameter: ±0.0003 in

0.1875 to 0.4375 in in diameter: ±0.0005 in

0.5000 to 1.5000 in in diameter: ±0.001 in

7.14.2 Metric drill rods

Metric drill rods are made of chrome vanadium alloy steel in 1-m lengths (approximately 39 in). Accuracy is metric h9. Heating for hardening: 1490–1580°F quench in oil; 1470–1510°F quench in water. Drawing temperatures: HRC-62, 400°F; HRC-60, 485°F; HRC-56, 570°F.

Available diameters. Metric drill rods are available in diameters ranging from 1 through 50 mm, in various steps or increments. Accuracy is metric h9.

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Chapter

8

Tooling, Die Making, Molds, Jigs, and Fixtures

8.1 Definitions

Tooling. *Tooling* is a general term used to encompass many different processes involving the design and manufacture of special tools, dies, molds, jigs, and fixtures. The most common type of tooling consists of dies that are used to stamp or blank sheet metal parts for mass production. The use of a stamping or blanking die makes it possible to produce thousands of parts with consistent dimensional accuracy at a rapid pace. This ensures that the die-produced parts will fit correctly into their next assembly stage, such as in a complex mechanical device or mechanism, and have interchangeability.

The production of detail parts from a tooling device such as a stamping die reduces the overall cost of producing industrial and consumer products in relation to the cost of the die versus the number of parts to be made on the die. Complex tooling devices are relatively expensive to produce and usually must be justified by the number of parts they produce during a set time interval. As a general rule, thousands of parts should be produced yearly to justify tooling costs and maintenance of the tools.

Die making. One of the most common tooling procedures is the design and production of dies, i.e., die making. Industry uses a great variety of dies, including

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- Stamping, blanking, and punching dies
- Bending and forming dies
- Combination or progressive dies
- Forging dies
- Dies for die casting metals and metal alloys
- Beading dies (a form of bending die)
- Extrusion dies
- Drawing dies (for wire, rod, and bar)
- Wire-form dies

Molds. There are many different types of molds that fall under the general definition of tooling. Molds are used to produce metal and metal-alloy parts and various types of plastic parts. In die casting, the mold is referred to as a "die." The various types of molds made from metals, usually tool steels, include

- Die-casting molds
- Chill-casting molds
- Permanent casting molds
- Slush-casting molds
- Thermoplastic injection molds
- Thermoset plastic compression molds

Molds are also made from special tooling epoxies (see Sec. 8.6.4).

Jigs. *Jigs* are defined as tooling devices used as patterns (templates) for producing parts, match plates for drilling holes, and other devices used to guide or control a machining process. The process of pin routing uses a template or jig to guide the action of the high-speed routing cutter while it is cutting a stack of thin-gauge sheet metal parts. A drilling or reaming jig may be designed to clamp previously die-stamped parts that are to receive a secondary machining operation such as reaming or additional drilling.

Specially hardened drill bushings are incorporated as part of the drill jig to guide the drill accurately as the part is jig drilled. Jigs allow parts to be produced with dimensional accuracy and consis-

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Tooling, Die Making, Molds, Jigs, and Fixtures

tency. Clamping and clamping devices are an important part of the jigging process. A subsection detailing clamping devices and clamping calculations will be presented in a later part of this chapter (see Sec. 8.8).

Fixtures. One of the most important aspects of tooling is the design and application of fixtures. A tooling *fixture* may be defined as a manufacturing aid or assembly device that is necessary in the production of mass-produced parts and assemblies. Various common types of fixtures are used in industrial applications, including

- Subassembly fixtures
- Assembly fixtures
- Welding fixtures
- Machining fixtures
- Wiring fixtures (for wire harnesses)

The design of tooling fixtures is limited only by the imagination and ingenuity of the tool designer. Fixtures for subassembly of small parts may weigh only a few ounces, whereas the assembly fixtures used to produce large aircraft and aerospace vehicles may weigh more than 100 tons. Tooling fixtures are an absolute necessity for the interchangeability of complex mass-produced products. Vast sums of money are spent each year by the automotive industry alone to produce the tooling fixtures required to assemble automotive equipment. The application of clamps and holding devices on tooling fixtures is an important part of tool design. The clamps and holding devices may be mechanical, electromechanical, pneumatic, or hydraulic and must be an integral part of the complete fixture. Safety and versatility must be kept in mind when designing the clamping and holding devices used on tooling fixtures.

8.2 Tool-Steel Characteristics, Heat Treatment, and Selection

To ensure that the proper tool steel is selected for each different type of tooling device and that its capabilities are developed to full potential, the producers of the various tool steels are prepared to advise tool designers or engineers on the mechanical properties and conditions of service under which the finished tools operate

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best. The word *tool* throughout this chapter denotes any of the tooling devices previously described.

The majority of tool-steel applications may be categorized under a small number of groups or types of operations: cutting, shearing, forming, drawing, bending, extruding, rolling, and ramming or battering. For each of these groups, certain metallurgic characteristics are of utmost importance. Cutting tools must possess high hardness and extreme strength, high resistance to the effects of elevated temperatures, and high wear resistance. Shearing tools require high wear resistance combined with toughness, and these characteristics must be balanced properly, depending on the tool design, thickness of the stock being sheared, and temperature of the shearing operation. Forming tools must possess high toughness and high strength, and many require high resistance to the softening effect of elevated temperatures. In battering or ramming tools, high toughness is the most important characteristic.

Heat treatment plays an important role in attaining these desired characteristics. It should be kept in mind that tools actually are being processed, not steels. To ensure that proper heat-treatment procedures are employed, this section will present tables that list guidelines for forging, annealing, hardening, tempering, and normalizing the commonly used tool steels to which American Iron and Steel Institute (AISI) designations have been assigned. These guidelines, which include temperature ranges, heating rates, cooling rates, and time at temperature, should be adapted to fit the specific application.

8.2.1 Identification and classification of tool steels

Figure 8.1 provides a list of the main tool-steel groups. Table 8.1 shows the identification and type classification of tool steels.

8.2.2 Heat treatment of tool steels

Tables 8.2 and 8.3 list the typical heat treatment of tool steels along with supplement notes and explanations (also see Sec. 4.1.1, "Tool Steels").

Tool steels are either carbon or alloy steels, which are capable of being hardened and tempered, and they are usually melted in electric furnaces and produced under tool-steel practices to meet their special requirements. Special care should be taken when using the

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Tooling, Die Making, Molds, Jigs, and Fixtures

Type of Tool-Steel	Designation
High-speed tool steels	M - molybdenum types T - tungsten types
Hot-work tool-steels	H H1 to H19 - chromium types H20 to H39 - tungsten types H40 to H59 - molybdenum types
Cold-work tool-steels	D - high-carbon high-chromium types A - medium-alloy air-hardening types O - oil-hardening types
Shock-resisting tool-steels	S
Mold tool-steels	P
Special-purpose tool-steels	L - low-alloy types F - carbon-tungsten types
Water-hardening tool-steels	W

Figure 8.1 Main tool-steel groups.

heat-treatment data shown in Tables 8.2 and 8.3, and this is outlined as follows.

Forging. The information shown in the tables is for those occasions when a consumer is unable to purchase the desired size and must forge from a larger size. The temperature at which to start forging is given as a range, the higher side of which should be used for larger sections and heavy or rapid reductions and the lower side for smaller sections and lighter reductions. As the alloy content of the steel increases, the time of soaking at forging temperatures increases proportionately. Likewise, as the alloy content increases, it becomes more necessary to cool slowly from the forging temperature. With very high alloy steels, such as high-speed steels and air-hardening steels, this slow cooling is imperative in order to prevent cracking. Either furnace cooling or burying in an insulating material, such as lime, mica, or silocel, is satisfactory.

Annealing. The information shown in the tables on annealing is intended for those instances where a finished tool must be softened for additional machining or where the user has performed a forging operation. The annealing temperature is given as a range, the

(Text continued on page 544.)

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TABLE 8.1 Identification and Type Classification of Tool Steels

Type	Identifying elements, % C	W	Mo	Cr	V	Co
High Speed: Tungsten Types (1)						
T1	0.75 (2)	18.00	—	4.00	1.00	—
T2	0.80	18.00	—	4.00	2.00	—
T4	0.75	18.00	—	4.00	1.00	5.00
T5	0.80	18.00	—	4.00	2.00	8.00
T6	0.80	20.00	—	4.50	1.50	12.00
T8	0.75	14.00	—	4.00	2.00	5.00
T15	1.50	12.00	—	4.00	5.00	5.00
High Speed: Molybdenum Types (1)						
M1	0.85 (2)	1.50	8.50	4.00	1.00	—
M2	0.85: 1.00 (2)	6.00	5.00	4.00	2.00	—
M3 class 1	1.05	6.00	5.00	4.00	2.40	—
M3 class 2	1.20	6.00	5.00	4.00	3.00	—
M4	1.30	5.50	4.50	4.00	4.00	—
M6	.80	4.00	5.00	4.00	1.50	12.00
M7	1.00	1.75	8.75	4.00	2.00	—
M10	0.85: 1.00 (2)	—	8.00	4.00	2.00	—
M30	0.80	2.00	8.00	4.00	1.25	5.00
M33	0.90	1.50	9.50	4.00	1.15	8.00
M34	0.90	2.00	8.00	4.00	2.00	8.00
M36	0.80	6.00	5.00	4.00	2.00	8.00
M41	1.10	6.75	3.75	4.25	2.00	5.00
M42	1.10	1.50	9.50	3.75	1.15	8.00
M43	1.20	2.75	8.00	3.75	1.60	8.25
M44	1.15	5.25	6.25	4.25	2.00	12.00
M46	1.25	2.00	8.25	4.00	3.20	8.25
M47	1.10	1.50	9.50	3.75	1.25	5.00

Type	Identifying elements, % C	Mn or Si	W	Mo	Cr	V	Co	Other
Cold Work: Medium-Alloy Air-Hardening Types (1)								
A2	1.00	—	—	1.00	5.00	—	—	—
A3	1.25	—	—	1.00	5.00	1.00	—	—
A4	1.00	2.00 Mn	—	1.00	1.00	—	—	—
A6	0.70	2.00 Mn	—	1.25	1.00	—	—	—
A7	2.25	—	1.00 (3)	1.00	5.25	4.75	—	—
A8	0.55	—	1.25	1.25	5.00	—	—	—
A9	0.50	—	—	1.40	5.00	1.00	—	1.50 Ni
A10 (4)	1.35	1.80 Mn: 1.25 Si	—	1.50 —	—	—	—	1.80 Ni
Cold Work: Oil-Hardening Types								
01	0.90	1.00	.50	—	.50	—	—	—
02	0.90	1.60	—	—	—	—	—	—
06 (4)	1.45	0.80 Mn: 1.00 Si	—	25	—	—	—	—
07	1.20	—	1.75	—	.75	—	—	—
—	—							
W5	1.10	—	—	—	0.50	—	—	—
Shock-Resisting Types								
S1	0.50	—	2.50	—	1.50	—	—	—
S2	0.50	1.00 Si	—	0.50	—	—	—	—
S5	0.55	0.80 Mn: 2.00 Si	—	0.40	—	—	—	—
S6	0.45	1.40 Mn: 2.25 Si	—	0.40	1.50	—	—	—
S7	0.50	—	—	1.40	3.25	—	—	—

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Hot Work: Chromium Types (1)						
H10	0.40	—	2.50	3.25	0.40	—
H11	0.35	—	1.50	5.00	0.40	—
H12	0.35	1.50	1.50	5.00	0.40	—
H13	0.35	—	1.50	5.00	1.00	—
H14	0.40	5.00	—	5.00	—	—
H19	0.40	4.25	—	4.25	2.00	4.25
Hot Work: Tungsten Types						
H21	0.35	9.00	—	3.50	—	—
H22	0.35	11.00	—	2.00	—	—
H23	0.30	12.00	—	12.00	—	—
H24	0.45	15.00	—	3.00	—	—
H25	0.25	15.00	—	4.00	—	—
H26	0.50	18.00	—	4.00	1.00	—
Hot Work: Molybdenum Types						
H42	0.60	6.00	5.00	4.00	2.00	—
Cold Work: High-Carbon High-Chromium Types (1)						
D2	1.50	—	1.00	12.00	1.00	—
D3	2.25	—	—	12.00	—	—
D4	2.25	—	1.00	12.00	—	—
D5	1.50	—	1.00	12.00	—	3.00
D7	2.35	—	1.00	12.00	4.00	—

Special-Purpose Low-Alloy Types								
L2	0.50/1.10 (5)	—	—	—	1.00	0.20	—	—
L6	0.70	—	—	0.25 (3)	0.75	—	—	1.50 Ni
Water-Hardening Types								
W1	0.60/1.40 (5)	—	—	—	—	—	—	—
W2	0.60/1.40 (5)	—	—	—	—	0.25	—	—
W5	1.10	—	—	—	0.50	—	—	—
Mold Types								
P2	0.07	—	—	0.20	2.00	—	—	0.50 Ni
P3	0.10	—	—	—	0.60	—	—	1.25 Ni
P4	0.07	—	—	0.75	5.00	—	—	—
P5	0.10	—	—	—	2.25	—	—	—
P6	0.10	—	—	—	1.50	—	—	3.50 Ni
P20	0.35	—	—	0.40	1.70	—	—	—
P21	0.20	—	—	—	—	—	—	4.00 Ni: 1.20 Al

(1) Some of the types can be produced with a sulfur addition to improve machinability.
(2) Other carbon contents may be available.
(3) Optional.
(4) Contains free graphite in the microstructure to improve machinability.
(5) Various carbon contents are available.

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Tooling, Die Making, Molds, Jigs, and Fixtures

TABLE 8.2 Typical Heat Treatments for Tool Steels

Tool steel type	Forging		Annealing			Hardening		
	Start, °F	Do not forge below °F	Temp., °F	Cooling rate, °F Max/h	Brinell hardness	Heating rate	Preheat temp., °F	Hardening temp., °F
High Speed: Tungsten Types								
T1	1950–2150	1750	1600–1650	40	217–255	Rapid from preheat	1500–1600	2300–2375(a)
T2	1950–2150	1750	1600–1650	40	223–255	Rapid from preheat	1500–1600	2300–2375(a)
T4	1950–2150	1750	1600–1650	40	229–269	Rapid from preheat	1500–1600	2300–2375(a)
T5	1950–2150	1800	1600–1650	40	235–285	Rapid from preheat	1500–1600	2325–2375(a)
T6	1950–2150	1800	1600–1650	40	248–302	Rapid from preheat	1500–1600	2325–2375(a)
T8	1950–2150	1800	1600–1650	40	229–255	Rapid from preheat	1500–1600	2300–2375(a)
T15	1950–2150	1800	1600–1650	40	241–277	Rapid from preheat	1500–1600	2200–2300(a)
High Speed: Molybdenum Types								
M1	1900–2100	1700	1500–1600	40	207–235	Rapid from preheat	1350–1550	2150–2225(a)
M2	1900–2100	1700	1600–1650	40	212–241	Rapid from preheat	1350–1550	2175–2250(a)
M3 (1; 2)	1900–2100	1700	1600–1650	40	223–255	Rapid from preheat	1350–1550	2200–2250(a)
M4	1900–2100	1700	1600–1650	40	223–255	Rapid from preheat	1350–1550	2200–2250(a)
M6	1900–2100	1700	1600	40	248–277	Rapid from preheat	1450	2150–2200(a)
M7	1900–2100	1700	1500–1600	40	217–255	Rapid from preheat	1350–1550	2150–2225(a)
M10	1900–2100	1700	1500–1600	40	207–255	Rapid from preheat	1350–1550	2150–2225(a)
M30	1900–2100	1700	1600–1650	40	235–269	Rapid from preheat	1350–1550	2200–2250(a)
M33	1900–2100	1700	1600–1650	40	235–269	Rapid from preheat	1350–1550	2200–2250(a)
M34	1900–2100	1700	1600–1650	40	235–269	Rapid from preheat	1350–1500	2200–2250(a)
M36	1900–2100	1700	1600–1650	40	235–269	Rapid from preheat	1350–1550	2225–2275(a)
M41	1900–2100	1700	1600–1650	40	235–269	Rapid from preheat	1350–1550	2175–2220(a)
M42	1900–2100	1700	1600–1650	40	235–269	Rapid from preheat	1350–1550	2125–2175(a)
M43	1900–2100	1700	1600–1650	40	248–269	Rapid from preheat	1350–1550	2100–2150(a)
M44	1900–2100	1700	1600–1650	40	248–285	Rapid from preheat	1350–1550	2190–2240(a)
M46	1900–2100	1700	1600–1650	40	235–269	Rapid from preheat	1350–1550	2175–2225(a)
M47	1900–2100	1700	1600–1650	40	235–269	Rapid from preheat	1350–1550	2150–2200(a)
Hot Work: Chromium Types								
H10	1950–2100	1650	1550–1650	40	192–229	Moderate from preheat	1500	1850–1900
H11	1950–2100	1650	1550–1650	40	192–235	Moderate from preheat	1500	1825–1875

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Tooling, Die Making, Molds, Jigs, and Fixtures

TABLE 8.2 Typical Heat Treatments for Tool Steels (*Continued*)

Hardening		Tempering					
Minutes at temp.	Quench medium (b)	Temp., °F	Tempered Rc hardness	Depth of hardening	Heat-treat distortion	Hardening safety	Resist. to decarb.
High Speed: Tungsten Types							
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	High	High
2–5	O, A, or S	1000–1100(c)	66–61	Deep	A or S = low; O = medium	High	High
2–5	O, A, or S	1000–1100(c)	66–62	Deep	A or S = low; O = medium	Medium	Medium to high
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100 (c)	65–60	Deep	A or S = low; O = medium	Medium	Medium
2–5	O, A, or S	1000–1200(c)	68–63	Deep	A or S = low; O = medium	Medium	Medium
High Speed: Molybdenum Types							
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	Medium	Medium
2–5	O, A, or S	1000–1100(c)	66–61	Deep	A or S = low; O = medium	Medium	Medium
2–5	O, A, or S	1000–1100(c)	66–61	Deep	A or S = low; O = medium	Medium	Medium
2–5	O, A, or S	1000–1100(c)	66–61	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100(c)	66–61	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100(c)	65–60	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1100(d)	70–65	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	950–1100(d)	70–65	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	950–1100(d)	70–65	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	1000–1160(d)	70–62	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	975–1050(d)	69–67	Deep	A or S = low; O = medium	Medium	Low
2–5	O, A, or S	975–1100(d)	70–65	Deep	A or S = low; O = medium	Medium	Low
Hot Work: Chromium Types							
15–40(e)	A	1000–1200(c)	56–39	Deep	Very low	Highest	Medium
15–40(e)	A	1000–1200(c)	54–38	Deep	Very low	Highest	Medium

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Tooling, Die Making, Molds, Jigs, and Fixtures

TABLE 8.2 Typical Heat Treatments for Tool Steels (*Continued*)

	Forging		Annealing			Hardening		
Tool steel type	Start, °F	Do not forge below °F	Temp., °F	Cooling rate, °F Max/h	Brinell hardness	Heating rate	Preheat temp., °F	Hardening temp., °F
H12	1950–2100	1650	1550–1650	40	192–235	Moderate from preheat	1500	1825–1875
H13	1950–2100	1650	1550–1650	40	192–229	Moderate from preheat	1500	1825–1900
H14	1950–2150	1700	1600–1650	40	207–235	Moderate from preheat	1500	1850–1950
H19	1900–2100	1650	1600–1650	40	207–241	Rapid from preheat	1500	2000–2200(a)
Hot Work: Tungsten Types								
H21	1950–2150	1650	1600–1650	40	207–235	Rapid from preheat	1500	2000–2200(a)
H22	1950–2150	1650	1600–1650	40	207–235	Rapid from preheat	1500	2000–2200(a)
H23	1950–2150	1800	1600–1650	40	212–255	Rapid from preheat	1550	2200–2300(a)
H24	1950–2150	1750	1600–1650	40	217–241	Rapid from preheat	1500	2000–2250(a)
H25	1950–2150	1700	1600–1650	40	207–235	Rapid from preheat	1500	2100–2300(a)
H26	1950–2150	1750	1600–1650	40	217–241	Rapid from preheat	1600	2150–2300(a)
Hot Work: Molybdenum Type								
H42	1900–2050	1700	1550–1650	40	207–235	Rapid from preheat	1350–1550	2050–2225(a)
Cold Work: High-Carbon High-Chromium Types								
D2	1850–2000	1700	1600–1650	40	217–255	Very slowly	1500	1800–1875
D3	1850–2000	1700	1600–1650	40	217–255	Very slowly	1500	1700–1800
D4	1850–2000	1700	1600–1650	40	217–255	Very slowly	1500	1775–1850
D5	1850–2000	1700	1600–1650	40	223–255	Very slowly	1500	1800–1875
D7	2050–2125	1800	1600–1650	40	235–262	Very slowly	1500	1850–1950
Cold Work: Medium-Alloy Air-Hardening Types								
A2	1850–2000	1650	1550–1600	40	201–235	Slowly	1450	1700–1800
A3	1850–1950	1650	1550–1600	40	207–229	Slowly	1450	1750–1850
A4	1850–2000	1650	1360–1400	25	200–241	Slowly	1250	1500–1600
A6	1900–2050	1600	1350–1375	25	217–248	Slowly	1200	1525–1600
A7	1925–2100	1800	1600–1650	25	235–269	Very slowly	1500	1750–1800
A8	1950–2100	1700	1550–1600	40	192–241	Slowly	1450	1800–1850
A9	1950–2100	1700	1550–1600	25	212–248	Slowly	1450	1800–1875
A10	1800–1925	1600	1410–1460	15	235–269	Slowly	1200	1450–1500
Cold Work: Oil-Hardening Types								
O1	1800–1950	1550	1400–1450	40	183–212	Slowly	1200	1450–1500
O2	1800–1925	1550	1375–1425	40	183–217	Slowly	1200	1400–1475
O6	1800–1950	1500	1410–1450	20	183–217	Slowly	—	1450–1500
O7	1800–2000	1600	1450–1500	40	192–217	Slowly	1200	W=1450–1525(b) O=1500–1625(b)
Shock-Resisting Types								
S1	1850–2050	1600	1450–1500	40	183–229	Slowly	1200	1650–1750
S2	1850–2050	1600	1400–1450	40	192–217	Slowly	1200	1550–1650
S5	1850–2050	1600	1425–1475	25	192–229	Slowly	1400	1600–1700
S6	1850–2050	1600	1475–1525	25	192–229	Slowly	1400	1650–1750
S7	1950–2050	1700	1500–1550	25	187–223	Slowly	1200–1300	1700–1750

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Tooling, Die Making, Molds, Jigs, and Fixtures

TABLE 8.2 Typical Heat Treatments for Tool Steels (*Continued*)

Hardening		Tempering					
Minutes at temp.	Quench medium (b)	Temp., °F	Tempered Rc hardness	Depth of hardening	Heat-treat distortion	Hardening safety	Resist. to decarb.
15–40(e)	A	1000–1200(c)	55–38	Deep	Very low	Highest	Medium
15–40(e)	A	1000–1200(c)	53–38	Deep	Very low	Highest	Medium
15–40(e)	A	1100–1200(c)	47–40	Deep	Low	Highest	Medium
2–5	A or O	1000–1300(c)	57–40	Deep	A = low; O = medium	High	Medium
			Hot Work: Tungsten Types				
2–5	A or O	1100–1250	54–36	Deep	A = low O = medium	High	Medium
2–5	A or O	1100–1250	52–39	Deep	A = low; O = medium	High	Medium
2–5	O	1200–1350(c)	47–34	Deep	Medium	High	Medium
2–5	O	1050–1200(c)	55–45	Deep	A = low; O = medium	High	Medium
2–5	A or O	1050–1250(c)	44–35	Deep	A = low; O = medium	High	Medium
2–5	O, A, or S	1050–1250(c)	58–43	Deep	S, A = low; O = medium	High	Medium
			Hot Work: Molybdenum Type				
15–45(e)	O, A, or S	1050–1200(c)	60–50	Deep	S, A = low; O = medium	Medium	Medium
			Cold Work: High-Carbon High-Chromium Types				
15–45(e)	A	400–1000	61–54	Deep	Lowest	Highest	Medium
15–45(e)	O	400–1000	61–54	Deep	Very low	High	Medium
15–45(e)	A	400–1000	61–54	Deep	Lowest	Highest	Medium
15–45(e)	A	400–1000	61–54	Deep	Lowest	Highest	Medium
30–60(e)	A	300–1000	65–58	Deep	Lowest	Highest	Medium
			Cold Work: Medium-Alloy Air-Hardening Types				
20–45(e)	A	350–1000	62–57	Deep	Lowest	Highest	Medium
25–60(e)	A	350–1000	65–57	Deep	Lowest	Highest	Medium
15–90(e)	A	350–800	62–54	Deep	Lowest	Highest	Medium to high
20–45(e)	A	300–800	60–54	Deep	Lowest	Highest	Medium to high
30–60(e)	A	300–1000	67–57	Deep	Lowest	Highest	Medium
20–45(e)	A	350–1100	60–50	Deep	Lowest	Highest	Medium
20–45(e)	A	950–1150	56–35	Deep	Lowest	Highest	Medium
30–60(e)	A	350–80	62–55	Deep	Lowest	Highest	Medium to high
			Cold Work: Oil-Hardening Types				
10–30	O	350–500	62–57	Medium	Very low	Very high	High
5–20	O	350–500	62–57	Medium	Very low	Very high	High
10–30	O	350–600	63–58	Medium	Very low	Very high	High
10–30	O or W	350–550	64–58	Medium	W = high O = very low	W = low O = very high	High
			Shock-Resisting Types				
15–45	O	400–1200	58–40	Medium	Medium	High	Medium
5–20	B or W	350–800	60–50	Medium	High	Low	Low
5–20	O	350–800	60–50	Medium	Medium	High	Low
10–30	O	400–600	56–54	Medium	Medium	High	Low
15–45(e)	A or O	400–1150	57–45	Deep	A = lowest; O = low	A = highest; O = high	Medium

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Tooling, Die Making, Molds, Jigs, and Fixtures

TABLE 8.2 Typical Heat Treatments for Tool Steels (*Continued*)

	Forging		Annealing			Hardening		
Tool steel type	Start, °F	Do not forge below °F	Temp., °F	Cooling rate, °F Max/h	Brinell hardness	Heating rate	Preheat temp., °F	Hardening temp., °F
Special Purpose: Low-Alloy Types								
L2	1800–2000	1550	1400–1450	40	163–197	Slowly	—	W=1450–1550 O=1550–1700
L6	1800–2000	1550	1400–1450	40	183–255	Slowly	—	1450–1550
Water-Hardening Types								
W1	1800–1950(f)	1500	1360–1450(f)	40	156–201	Slowly	(g)	1400–1550(h)
W2	1800–1950(f)	1500	1360–1450(f)	40	156–201	Slowly	(g)	1400–1550(h)
W5	1800–1950(f)	1500	1360–1450(f)	40	163–201	Slowly	(g)	1400–1525(h)
						Hardening		
						Carburizing temp., °F		Hardening temp., °F
Mold Types								
P2	1850–2050	1550	1350–1500	40	103–123	1650–1700		1525–1550(i)
P3	1850–2050		1350–1500	40	109–137	1650–1700		1475–1525(i)
P4	1850–2050	1600	1600–1650	25	116–128	1775–1825		1775–1825(i)
P5	1850–2050	1550	1550–1600	40	105–131	1650–1700		1550–1600(i)
P6	1950–2150	1700	1550	15	183–217	1650–1700		1450–1500(i)
P20	1850–2050	1600	1400–1450	40	149–212	1600–1650		1500–1600
						Solution Treating		
						Heating rate	Preheat temp.	Solution temp., °F
P21	2000–2100	1750		Do not anneal		Slowly	Do not preheat	1300–1350

upper limit of which should be used for large sections and the lower limit for smaller sections. The length of time the steel is held, after being uniformly heated through at the annealing temperature, varies from about 1 hour for light sections and small furnace charges of carbon or low-alloy tool steel to about 4 hours for heavy sections and large furnace charges of high-alloy steel.

Normalizing. The purpose of normalizing after forging is to refine the grain structure and to produce a uniform structure throughout the forging. Normalizing should not be confused with low-temperature (about 1200°F) annealing, which is used for relief of residual stresses resulting from heavy machining, bending, and forming.

Steels that can be normalized are O1 (1600°F), O2 (1550°F), O6 (1600°F), and O7 (1650°F); L2 (1600-1650°F) and L6 (1600°F); WI, W2, and W5 (1450-1700°F); and P20 and P21 (1650°F).

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Tooling, Die Making, Molds, Jigs, and Fixtures

TABLE 8.2 Typical Heat Treatments for Tool Steels (*Continued*)

Hardening		Tempering					
Minutes at temp.	Quench medium (b)	Temp., °F	Tempered Rc hardness	Depth of hardening	Heat-treat distortion	Hardening safety	Resist. to decarb.
Special Purpose: Low-Alloy Types							
10–30	O or W	350–1000	63–45	O = medium	O = medium W = high	O = medium W = low	High
10–30	O	350–1000	62–45	Medium	Low	High	High
Water-Hardening Types							
10–30	B or W	350–650	64–50	Shallow	High	Low	Highest
10–30	B or W	350–650	64–50	Shallow	High	Low	Highest
10–30	B or W	350–650	64–50	Shallow	High	Low	Highest
Mold Types							
15	O	350–500	64–58(k)	Medium	Low	High	High
15	O	350–500	64–58(k)	Medium	Low	High	High
15	A	350–900	64–58(k)	Medium	Very low	High	High
15	O or W	350–500	64–58(k)		W = high O = low	High	High
15	A or O	350–450	61–58(k)		A = very low, O = low	High	High
15	O	900–1100	37–28	Medium	Low	High	High
		Aging					
		Temp., °F	Hardness Rc				
60–180	A or O	950–1025	40–30	Deep	Lowest	Highest	High

The length of time the steel is held after being uniformly heated through at the normalizing temperature varies from about 15 minutes for a small section to about 1 hour for large sizes. Cooling from the normalizing temperature is done in still air.

Other factors of concern to heat treaters. Other properties of the tool steels that are of concern to the heat treater are depth of hardening, distortion in heat treating, safety in hardening, and resistance to decarburization. A qualitative evaluation of these properties is also presented in Tables 8.2 and 8.3, comparing all the tool steels relative to one another rather than within any particular class. The following general observations may be helpful.

Depth of hardening. This relates to the depth of hardness penetration of the individual tool steels. The hardenability ratings are based

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TABLE 8.3 Notes and Explanations for Table 8.2

(a) When the high temperature heating is carried out in a salt bath, the range of temperatures should be about 25°F lower than that shown.

(b) A = air quench
B = brine quench
O = oil quench
S = salt bath quench
W = water quench

(c) Double tempering recommended for not less than 1 h at temperature each temper.

(d) Triple tempering recommended for not less than 1 h at temperature each temper.

(e) Times shown apply to open furnace heat treatment. For pack hardening, a common rule is to heat for ½ h per inch of cross section of the pack.

(f) Forging, normalizing, and annealing temperatures of carbon tool steels are given as ranges because they vary with carbon content. The following temperatures are recommended:

Forging
0.50 to 1.25% C: the range shown
1.25 to 1.40% C: low side of range

Normalizing
0.60 to 0.75% C: 1500°F
0.75 to 0.90% C: 1450°F
0.90 to 1.10% C: 1600°F
1.10 to 1.40% C: 1600 to 1700°F

Annealing
0.60 to 0.90% C: 1360 to 1400°F
0.90 to 1.40% C: 1400 to 1450°F

(g) For large tools and tools having intricate sections, preheating at 1050–1200°F is recommended.

(h) Varies with carbon content as follows:
0.60–0.80% C: 1450–1550°F
0.85–1.05% C: 1425–1550°F
1.10–1.40% C: 1400–1525°F

(i) After carburizing

(k) Carburized case hardness

SOURCE: "AISI Steel Products Manual—Tool Steels," April 1976.

on the use of the particular quenching medium recommended. Carbon tool steels in group W are very shallow hardening steels and generally are quenched in water. The hardenability increases in tool steels as the alloy content increases (except for cobalt and tungsten). The hardenability increases with carbon content until excess carbide appears, and then it begins to decrease with further increases in carbon. For large tool or die sections, it is imperative that a high-alloy steel be selected if high strength is to be developed throughout the section in the finished part. For the P steels that are used in the carburized and hardened condition, the core hardenability is rated as low, medium, or high.

Distortion in heat treating. This rates the tool steels on the basis of the distortion normally obtained in hardening the respective grades

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from the normally recommended hardening temperatures. Distortion in heat treating is important in intricately designed tools that must maintain their shape after hardening. The steels rated lowest or very low usually can be machined very close to finish size prior to heat treatment so that little grinding will be required after the hardening operation.

In general, water-hardening steels exhibit the most distortion, whereas air-hardening steels exhibit the least. It is important to note, however, that carbon tool steels and other shallow-hardening types may distort very little in heat treatment when the hardened case is small in comparison with the unhardened core for any particular tool or die design.

Safety in hardening. This deals with the overall freedom from heat-treating difficulties that may be experienced in handling the tool-steel grades in question. The ratings apply particularly to freedom from cracking when complicated or intricate sections are being hardened. The air- and oil-hardening steels prove superior to the water-hardening steels in this respect.

When designing machine parts and tools that require heat treatment, the design engineer should allow generous filleting at changes in section and eliminate the use of sharp angles as far as possible. The greater the symmetry of design, the less hazardous is the heat treatment.

Resistance to carburization. This influences the type of heat-treating equipment selected, as well as the amount of material that should be removed from the surface after hardening. Both these factors concern the economics of tool-steel use. The ratings are intended to apply at the hardening temperature normally recommended. Those steels which are rated low must be protected in some way from decarburization during the heating cycle.

Additional heat-treatment data. See Sec. 4.1.1.

8.2.3 Selection of tool steels

The tool steels listed in the preceding tables are generally available. The relative availability within a group, however, will vary depending on whether the steel is designed for specific applications or finds use in general applications. Experience indicates that in most cases the choice is not limited to a single type of tool steel or even to a particular family of tool steels for a workable solution to an individual

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tooling problem. It is desirable to select a tool steel that will give the most economical overall performance when weighed against expected productivity, ease of fabrication, and cost.

The majority of tool-steel applications can be divided into a small number of groups or types of operations, such as cutting, shearing, forming, drawing, extruding, rolling, and battering. The following characteristic descriptions of the tool steels are intended as a guide, and it must be understood that the proper selection of a tool steel for a specific application cannot always be made with 100 percent assurance. Because of this, consultation with the steel producer is recommended. The following list describes the characteristics of the major tool-steel types.

A. Cold-work tool steels (medium alloy, air hardening). These steels show a minimum of distortion during heat treatment and have greater safety in hardening than the oil-hardening grades. Dies that could crack during heat treatment when made from oil-hardening grades generally can be handled safely when made from the air-hardening group. The low-carbon types A8 and A9 offer greater shock resistance than the other steels in this group but are lower in wear resistance. Type A7 exhibits maximum abrasion resistance but should be restricted to lower-toughness applications.

D. Cold-work tool steels (high carbon, high chromium). These steels are more wear resistant than the medium-alloy air-hardening steels used where long-run dies are required. Of the group, Dl, D2, and D5 have the greater toughness but the least abrasion resistance. These steels, being very wear resistant, are difficult to machine and grind, and a minimum of stock should be allowed for grinding after hardening. These grades are all air hardening and show little distortion or movement during heat treatment. Wear resistance increases as the carbon and vanadium contents increase.

E. Special-purpose tool steels (carbon-tungsten types). These are often called *finishing steels* and provide relatively high wear resistance in water-hardening steels. These steels typically are used for wire, bar, or tube cold-drawing dies, finishing tools, and fine-cutting-edge tools such as broaches, taps, and reamers. F2 is recommended where high wear resistance and sharp-cutting-edge capability are required. These steels are somewhat difficult to grind after hardening because of their wear and abrasion resistance.

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H. Hot-work tool steels. These steels are chromium-, tungsten-, and molybdenum-based. The chromium-based types are air hardening, showing very little distortion during heat treatment. The tungsten- and molybdenum-based steels are either air or oil hardening and show more distortion during oil quenching. These are high-heat-resisting steels with moderate wear resistance. The tungsten types (H2O to H39) are for those hot-work applications where resistance to the softening effect of elevated temperature is of greatest importance and a lesser degree of toughness is allowed. The molybdenum types (H40 to H59) offer excellent high-heat resistance but should be restricted to those applications where less ductility is acceptable. A wide range of hot-work tools are made from these steels for die-casting dies, extrusion-press parts, forging dies, hot punches, and shears.

I. Special-purpose tool steels (low alloy). These steels have deeper hardening characteristics than the W group and have similar properties to O1 and O2 as general-purpose tool steels but exhibit a greater tendency to distort during heat treatment. Of the group, L6 has greater toughness, at the sacrifice of wear resistance. High-carbon type L3 may be used for short-run and special-purpose tools and dies.

M. High-speed tool steels (molybdenum base). These steels are used commonly for high-speed cutting tool applications. They decarburize better than the tungsten type and are somewhat more critical in their heat treatment. Vanadium and cobalt are added, as is the case with the tungsten types, with corresponding advantages and disadvantages. The M2 type is considered the molybdenum counterpart of T1 as a general-purpose cutting tool material. The series beginning with M41 has the characteristic of exceptionally high hardness in heat treatment. These steels are also used for cold-header die inserts, punches, and thread-rolling and blanking dies. The steels in this group are underhardened for these applications in order to increase toughness.

O. Cold-work tool steels (oil hardening). All these steels listed under the symbol O are low-alloy types that must be oil quenched in heat treatment. Types O1 and O2 are widely used tool steels for many types of die applications, having greater hardenability and generally less distortion during heat treatment than the water-hardening steels. These steels will harden throughout in sections up to 2.50 in thick with relative freedom from distortion and cracking during heat treatment. Type O7 attains the greatest wear or abrasion resistance but is usually used in special applications.

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P. Special-purpose tool steels (mold steels). These steels are generally considered as plastic-mold steels but have found other applications outside the mold-making field. These steels are usually supplied at very low hardness to facilitate machining and other processing prior to carburizing to develop the required surface properties for injection and compression molds for plastics. Types P20 and P21 are usually supplied in the hardened condition so that they may be machined and put into immediate service. These types are suitable for plastic molds, zinc die-casting dies, and holder blocks.

S. Shock-resisting tool steels. These steels contain less carbon but higher alloy content and therefore are tougher than water-hardening grades. They have less wear resistance than the water-hardening steels but are used where punching, shearing, or trimming is being performed. Type Sl has the greatest wear resistance in the group and may be carburized for even greater hardness and wear resistance, but with a loss in toughness. Because of the moderately high hardening temperatures and rapid quenching required, these steels are subject to distortion during heat treatment.

T. High-speed tool steels (tungsten base). These steels generally are used for metal-cutting tools, although type T1 is sometimes used as a die material because of its high strength and wear resistance. Type T1 has been an established general-purpose high-speed steel (HSS) for many years.

W. Water-hardening tool steels. Being low in alloy content, these steels are shallow hardening, developing a tough case with a hard core. They are quenched in water or brine, are subject to distortion, and do not retain their properties above 350°F. Water-hardening tool steels are used for short production runs in all types of tools and dies. Their shallow hardenability adapts them well for cold-heading dies. Although used for many applications, they are limited in their properties and capabilities.

8.3 Dies, Molds, and Die-Making Procedures

The stamping, punching, or blanking die is the most common type of tooling employed by industry. These types of dies consist of a male punch and a female die block. The material to be punched, stamped, or blanked is placed between the die sections, and a force

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is applied to the punch or male portion of the die set. As the material is being punched, compressive and tensile stresses are developed within the stock material until a cutting and then shearing action takes place, forcing the punched portion of the material out of the female die block. Figure 8.2 illustrates a typical punching operation.

A portion of the stock is cut cleanly, whereas the remainder is broken by the shear forces developed within the material. Figure 8.3 shows a typical punched edge with the cut and sheared sections clearly defined. The shiny section is the cut portion, whereas the remainder is shear-fractured. The proportion of the cleanly cut section in relation to the irregular shear-fractured section is a function of the material hardness and the die clearance. Soft materials will have approximately 30 percent or more of the stock cut and the remainder shear-fractured, whereas hard materials will have only

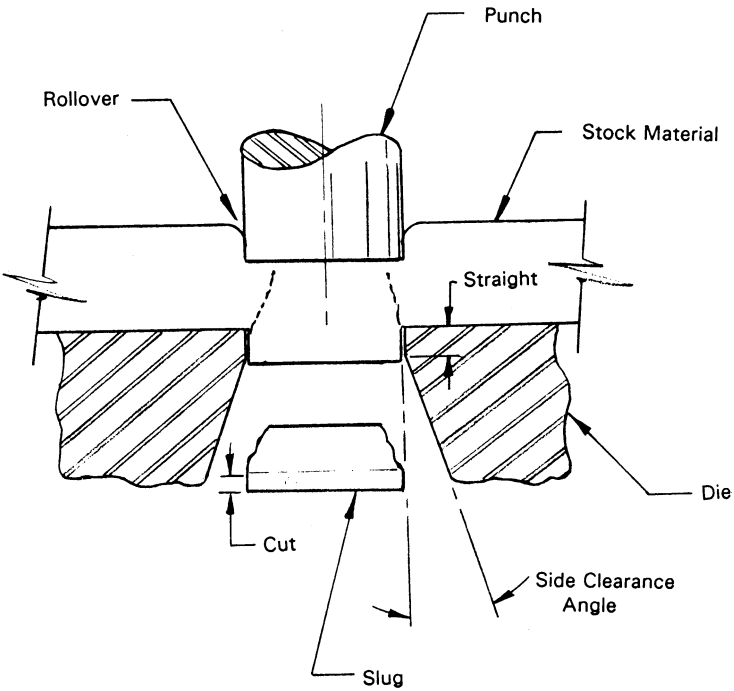

Figure 8.2 Punch action.

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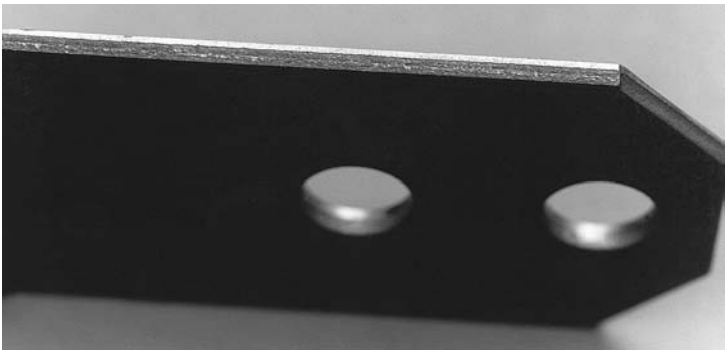

Figure 8.3 Punched edge.

10 to 20 percent of the stock thickness cleanly cut and the remainder shear-fractured.

The female die block must have an angular side clearance below the die-cutting straight in order for the punched part to fall out or clear the female die after the punching operation is completed. Figure 8.4 shows a typical blanking die set, separated to show the parts. In the figure, the parts of the die set are labeled and defined as follows:

A: Male portion of die

B: Top plate of the die set

C: Guidepost bushing

D: Bottom plate of the die set

E: Gate (for stock material)

F: Stripper or shoulder bolt

G: Opening in stripper plate

H: Guidepost

I: Die spring

J: Female die

K: Stripper plate

The die set shown in Fig. 8.4 was designed and built for blanking polycarbonate (Lexan) plastic material, 0.05 in thick. The plastic

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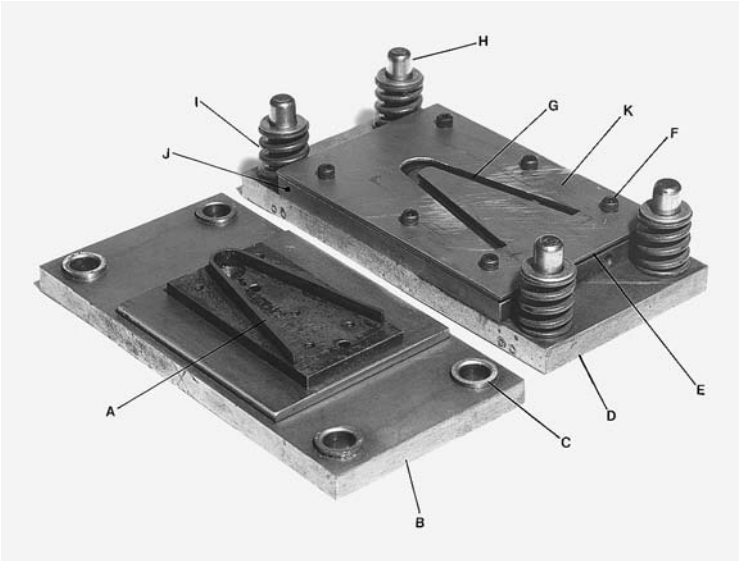

Figure 8.4 Blanking die, separated.

stock was cut in uniform strips to fit the die gate so that it could be fed progressively into the die during each blanking operation with the production of a minimum amount of scrap.

8.3.1 Manual die making (blanking dies)

Prior to the modern electric discharge machining (EDM) methods of punching and blanking, the die maker used the manual method, which consisted of the following process steps:

1. The male portion or punch section of the die was machined to the proper shape and dimensions from the selected tool steel.
2. The finished male portion or punch was then heat-treated to the required hardness and temper.
3. The heat-treated male portion was then set against the face or surface of the soft or annealed female die block and a high pressure applied. This step produced a sharp outline of the male portion into the surface of the female die block.

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4. The die maker then machined the female die block close to the outline impression made by step 3 (to within a few thousandths of an inch).

Note: The male portion and female die block were drilled and pinned (mounted) into the die set prior to step 3.

5. With the male and female portions aligned and set, pressure was applied to the die set, forcing the male portion into the female die block a small distance. This procedure shaved the close machined edges of the female die block and rolled the die material inward.
6. The female portion then was hand filed carefully to remove the rolled and shaved burrs produced by step 5.
7. Step 6 was repeated until the male portion had progressed into the female die block by approximately two times the thickness of the stock material to be stamped.
8. The correct side clearance angle was then filed in the female die block, below the cutting straight. Angular side clearances range between 0.5 and 2.00 per side, according to stock thickness. The height of the cutting straight is 0.125 in for all stock 0.125 in thick and less and usually equal to the stock thickness for all stock above 0.125 in.
9. The proper die clearance was then applied to the male punch or female die block by hand filing the appropriate die member.

Note: As a general rule in die stamping or punching,

- For punching holes in parts, the punch (male) is made to the exact size of the punched hole or area, and the correct die clearance is filed or cut in the female die block (Fig. 8.5*a*).
- For stamping or blanking a part outline, the female die block is made to the exact part size, and the punch (male) is filed smaller according to the required die clearance (Fig. 8.5*b*).

8.3.2 EDM (electric-discharge machining) die-making procedures

Electric-discharge machining (EDM) has replaced much of the work of the die maker in many companies where EDM machines are employed. In the EDM process, which includes both wire and ram

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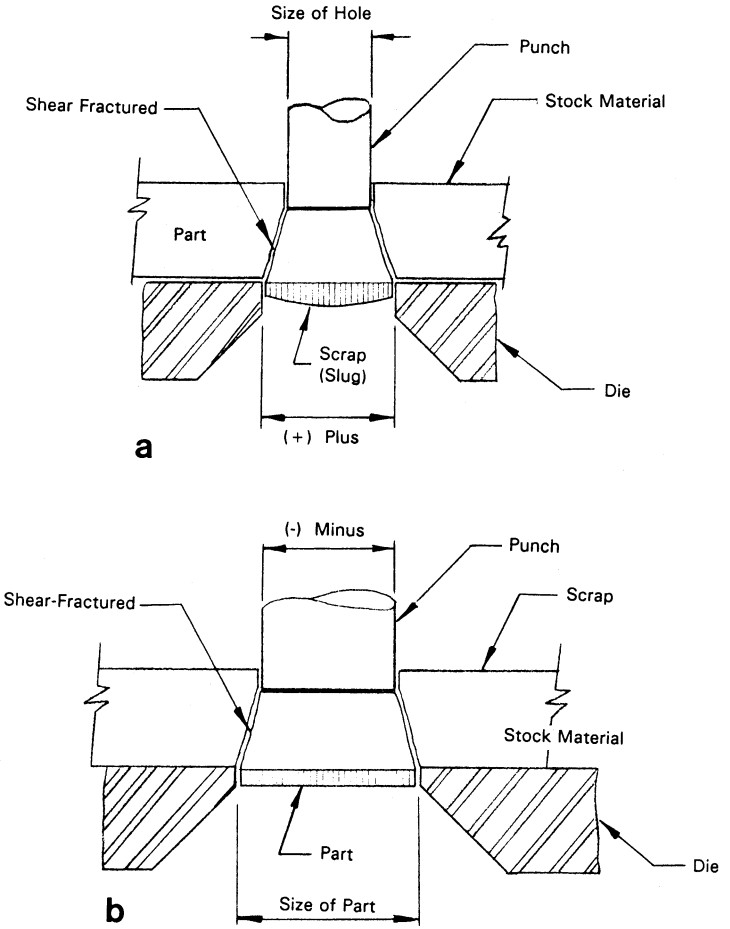

Figure 8.5 (*a*) Punching holes. (*b*) Punching a part

methods, an electrically charged electrode (wire or solid form) does the actual cutting of the metal (usually tool steel). The hand production of dies is still practiced where the cost of an EDM machine cannot be justified on a production basis.

The wire EDM machine is usually employed when making punching and blanking dies with complex outlines, where extreme accuracy is required. As an example of the accuracy of the EDM wire process,

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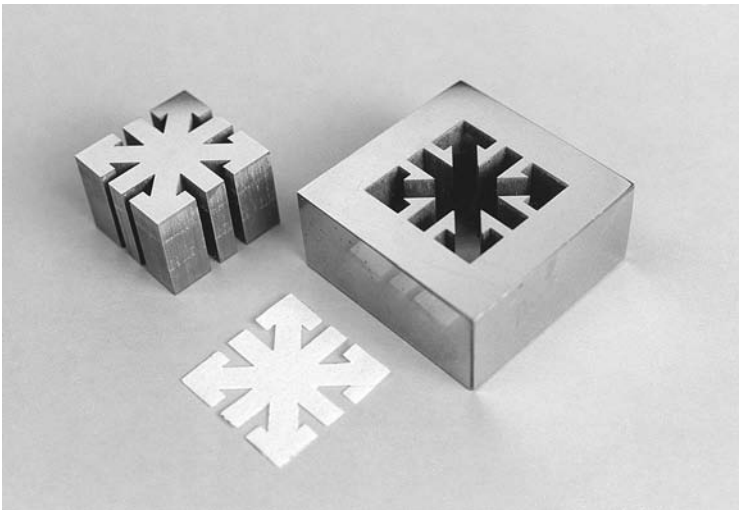

Figure 8.6 A sample die set, wire EDM cut from hardened tool steel.

see Fig. 8.6. The die set in the figure was manufactured (wire EDM cut) of prehardened tool steel and was produced in less than 8 hours. The hand production of a small die set with a complex shape such as that shown in the figure would have taken an expert die maker as long as 5 to 8 days of tedious work. This small sample die set was cut with a total die clearance of 0.0005 in and is capable of punching a thin sheet of paper. The only additional work required after wire EDM cutting of the male and female portions was to surface grind the two die parts. The two portions of the die are separated and shown with a thin piece of paper, which was cut using hand pressure. A die set such as this would be difficult to produce by manual methods of die making owing to its small size and intricate pattern.

Another example of EDM is given in Fig. 8.7, which shows the teeth of a ratchet that was wire cut from 0.188-in-thick cold-rolled steel sheet stock. The sharp edges of the ratchet teeth are typical of an EDM-cut material. The movements of the EDM machine are determined by a computer numerical control (CNC) controller on the machine that has been programmed by the tool engineering department. The program to cut this ratchet was loaded into the EDM machine's controller memory and the program run to produce the part to great accuracy. The holes shown in the ratchet were die-punched after the teeth were EDM cut.

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Figure 8.7 A ratchet plate, CNC EDM wire cut from mild steel. Note the sharp, accurate cut edges.

The wire EDM machines produced in the 1980s have been improved to the point where the cutting speeds have increased two to four times their original rates. The cutting section of a typical wire EDM machine is shown in Fig. 8.8. The wire can be seen running vertically between the wire guides and feed mechanism. During the cutting operation, cutting/cooling fluid is allowed to flow over the part in the vicinity of the wire, where it contacts the material being cut. When tool steels are being cut on the wire EDM machine, they may be cut in the annealed condition and later heat-treated, or they may be cut in the fully hardened condition to prevent the distortion that may occur during heat treatment. This characteristic of wire EDM cutting allows the tool engineer to use grades or types of tool steels for die making that otherwise would distort in heat treatment by cutting the dies in the fully hardened condition.

The newer types of wire EDM machines are designed so that the wire guides are controlled independently and are able to move so that tapered sides may be cut into the die. Thus a conical slug or other taper-sided outline can be cut from a die block.

EDM die-making procedures are similar to the manual method of making dies, except that tool-steel die members (punch and die block) are produced on the wire EDM machine, with the tool steel

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Figure 8.8 Close-up of wire EDM. Note the wire guides.

either being heat treated or in the soft condition. It is usually found that the wire EDM machine will cut the tool-steel die members cleaner when they are in the fully heat-treated condition.

After the die members have been cut with the proper die clearance, the die parts are mounted in the die set with shims placed around the mated male and female die members to ensure that the die clearance is the same all around. The dies are then drilled and pinned, with additional shoulder bolts or socket-head cap screws employed besides the alignment pins to hold all the members securely in alignment.

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The basic die set consisting of top and bottom plates (die shoe), guideposts, and guide bushings plus an optional top shank may be ordered in many different styles and sizes from suppliers such as Danly or Dieco and others. Photographs and illustrations of typical standard and special die sets are shown in other subsections.

8.3.3 EDM mold making (ram EDM)

Molds that are machined from tool steels are presently being made using ram EDM machines. In this process, the cavity of the mold is produced in a positive shape from a carbon-type material. This form, or "positive," is then used in the ram EDM process to machine the cavity of the mold by the electric-discharge process. The ram, or electrode (positive form), is placed under a cutting/cooling fluid with the tool-steel mold block and is moved downward into the tool steel block as the electric-discharge cutting operation progresses. A hollow or cavity with the exact shape of the ram or electrode thus is produced to great accuracy with a fine surface finish on the tool-steel mold block.

Molds or dies are produced with this method for manufacturing plastic parts (injection or compression molding process), as well as for die casting and powder-metal processing. Large amounts of material are machined accurately at a relatively rapid rate in the newer ram EDM process. When the mold cavities have been cut, the die or mold maker must polish the mold and add gates, ejectors, and other requirements to complete the final mold assembly. The P-type special-purpose tool steels usually are selected for production of molds for plastic parts, whereas other types of tool steels are selected for die-casting dies, permanent steel molds, and powder-metal dies.

8.3.4 Samples of dies, drawings, and stamped or blanked parts

A typical high-quality die set is shown in Fig. 8.9. This is a heavy-duty, long-production-run type of stamping die for producing heavy-gauge cold-rolled steel parts. The male and female die element tool-steel materials were selected and heat treated with great care and assembled accurately by the die maker. The tool-steel die elements were cut on the wire EDM machine using a sophisticated CNC program designed by the tool engineering department. The CNC program was then loaded into the EDM machine's controller and the dies accurately cut, with the tool-steel die elements having been heat treated previously.

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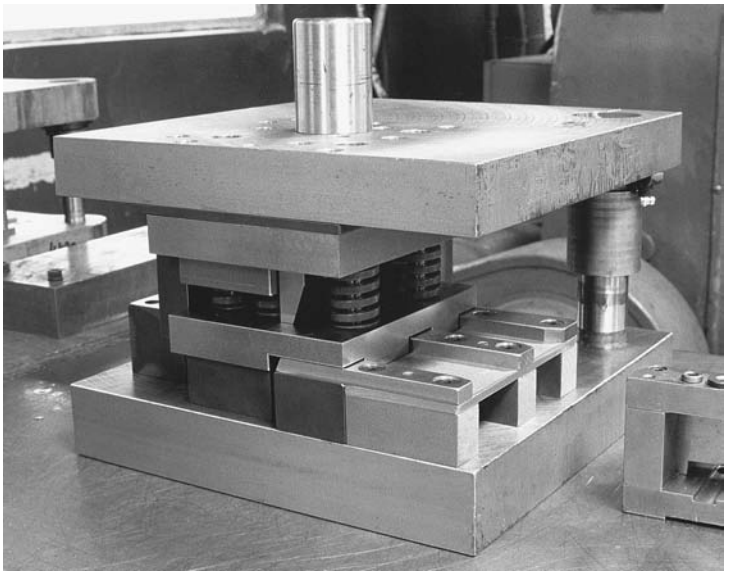

Figure 8.9 A typical high-quality blanking die set.

Figure 8.10 shows another finished die set with its required protective shield surrounding the die. Industry regulations call for protective shields on dies where an operator may accidentally come into hand contact with the moving parts of the die during the blanking, punching, forming, or drawing operations. The design and addition of the protective die shields are an important part of die design today and are necessary for worker safety.

Figure 8.11 shows two typical blanked parts. The upper part in the figure is made of a low-strength aluminum alloy (3003-H14), and the 50 percent cut or burnished section can be seen over the shear-fractured section. The part below is made of C-1018 cold-rolled steel, and a double cut or burnish is evident. The double cut alternating between the shear-fractured areas is characteristic of a close die clearance per side of 1 to 2 percent of the total stock thickness. This type of blanked edge may not be suitable for certain types of applications, and a secondary operation such as shaving may be required to finish the part edges.

In Sec. 8.5.1 figures will be presented for calculating the tonnage required on the press for stamping parts. To calculate the tonnage requirements, we must know the perimeter of the part in linear

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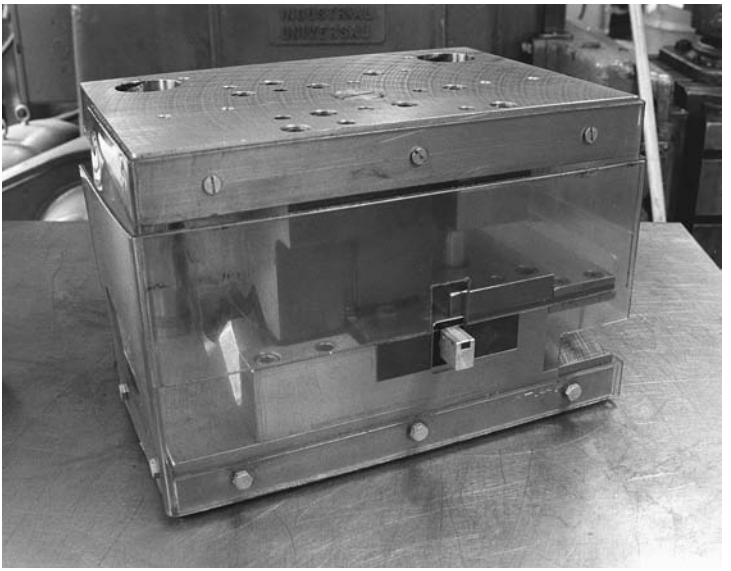

Figure 8.10 Finished die set with required hand protection shield (clear Lexan plastic).

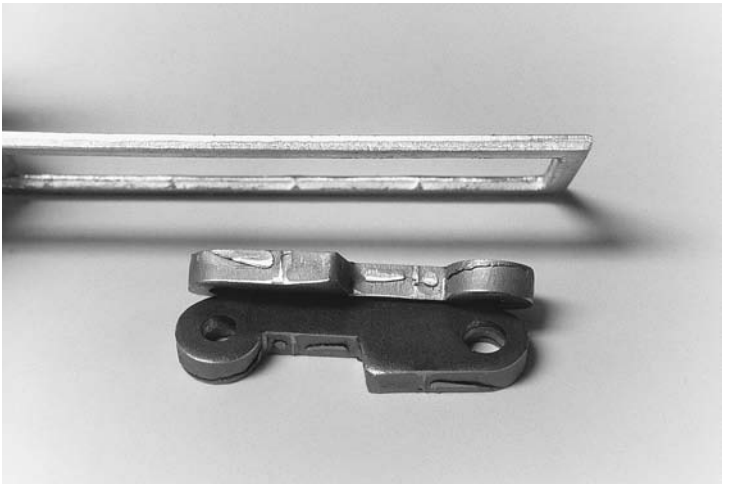

Figure 8.11 Typical blanked parts, edge characteristics.

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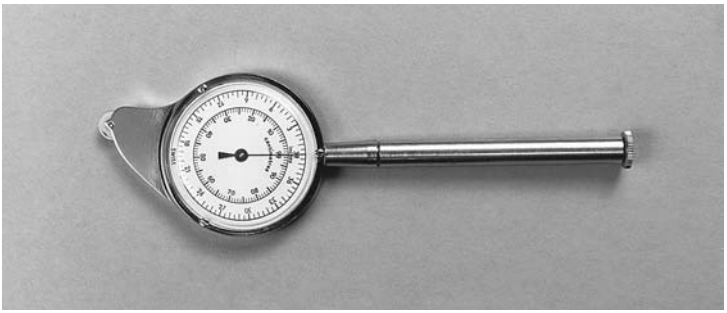

Figure 8.12 Linear measuring device.

inches or millimeters. Figure 8.12 shows a measuring tool used to determine the perimeter of irregularly shaped parts. This tool is sometimes called a *map measuring tool*. To use the tool, the scale is zeroed, and the small wheel at the end of the tool is placed at a starting point on the perimeter of the part to be measured. Tracing the tool around the perimeter of the part by rolling the wheel on the part outline will give a direct scale measurement in inches or millimeters on the dial of the tool. From this measurement, the tonnage requirements may be calculated using procedures shown in a later section.

The modern die-making and design processes use CNC and computer programs not only to control the EDM machines but also to produce the die drawings. A computer-generated drawing is possible using the various computer-aided design (CAD) systems available today. The CAD program sends the output information for the drawing to a plotter or laser printer, where a clean, neat drawing is produced. Figure 8.13 presents an example of a CAD drawing produced by a modern tool and die design and engineering department.

8.3.5 Steel-rule dies

Steel-rule dies make use of low-cost materials and are employed in many industrial applications. These are single-element tools that consist of a steel-rule cutting section only. Printers rule or similar steel strip is employed and bent to the shape of the part to be punched or cut. The sharp edges of the steel-rule members are operated against a flat metal platen or a hard wood or plastic block and produce the blanked part by a cutting or cleaving action.

Steel-rule dies are used to blank paper, cardboard, fiber, rubber, felt, leather, and similar materials (gaskets are a good example).

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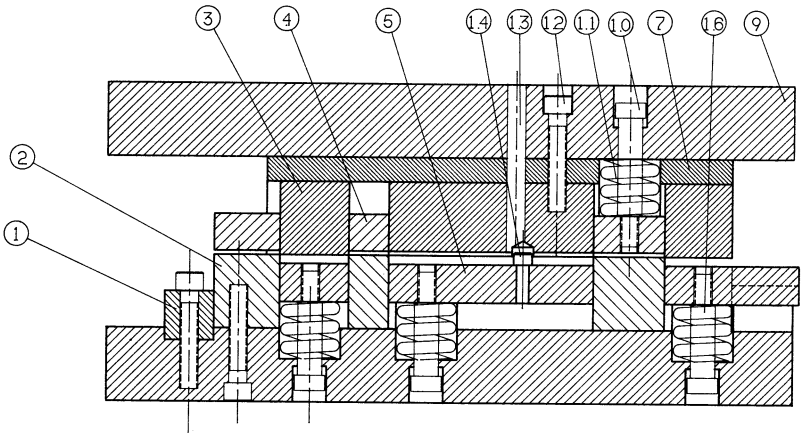
Tooling, Die Making, Molds, Jigs, and Fixtures

SECTION -A-A



.					
.17	1	PIVOT	CRS	.938x1.25x4.0	
.16	5	STRIPPER BOLT	9-0814-68	1/2#x1.75	DANLY
.					
.14	2	LOCATOR	02 STEEL	.360#x1	
.13	6	DOWEL PIN	.375x2 1/4	.376#x2.5	DANLY
.12	22	SHCS	3/8-16x2	3/8-16x2	DANLY
.11	12	SPRING	9-2008-28	1 1/4#x1 1/2	DANLY
.10	6	STRIPPER BOLT	9-0816-68	1/2#x2	DANLY
.9	1	DIE SET	1410-2F-1	#1410-2F-1	DANLY
.					
.7	1	SPACER	CRS	1/2x8.312x9.497	
.6	1	DIE	A2-464	1.5x5.281x8.9	60...62
.5	1	PRESSURE PAD	CRS	3/4x8 6/16x10.475	
.4	1	STRIPPER	A2-464	3/4x7 5/16x9.187	
.3	1	PUNCH	A2-464	1.5x8.375x9.497	58...60
.2	1	DIE	A2-464	1.5x3.29x9.187	60...62
.1	4	KEY	CRS	1x1x8	
POS	QTY	PART NAME	MATERIAL	DIMENSIONS	HARDNESS

Figure 8.13 Typical CAD drawing of a die set.

Figure 8.14 shows an exploded view of steel-rule die construction. The steel rules that do the actual cutting should be hardened to Rockwell C 52 to C 55, although this high a hardness may not be required for some materials. The stripper portion of the die is usually 0.312 to 0.375 in thick, extending slightly above the height of the steel-rule cutters, and is made of neoprene, cork sheet, or rubber.

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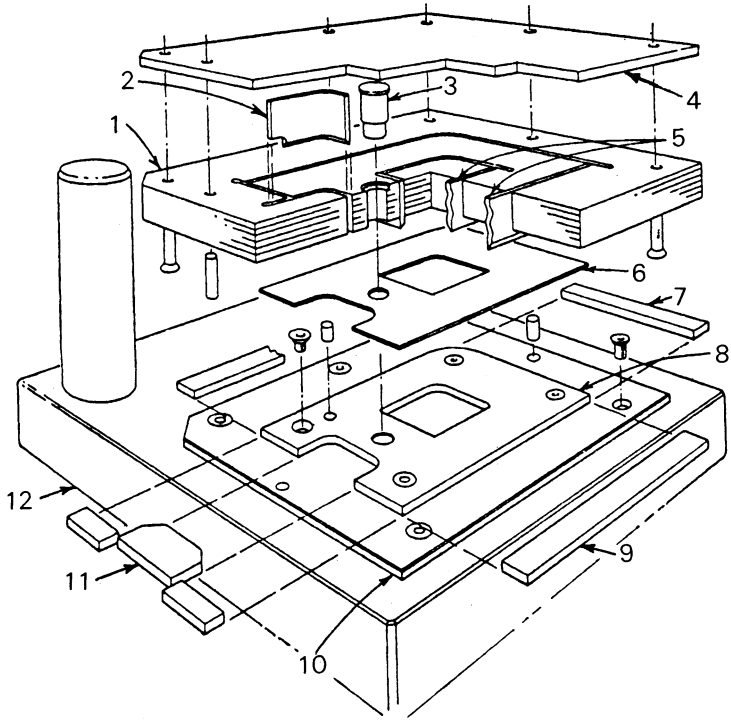

1	Plywood	7	Neoprene
2	Steel rule	8	Die plate
3	Punch	9	Neoprene
4	Steel subplate	10	Steel subplate
5	Steel rule	11	Neoprene
6	Blank	12	Die shoe

Note: Neoprene inserts are cut and glued in those areas where stripping action is required.

Figure 8.14 Typical steel-rule die.

8.4 Die Clearances and Stamping Data

Figure 8.15 shows the different types of edges produced on punched and blanked parts with different die clearances. This figure is typical of the low-carbon steels, which are used frequently for many types of die-stamped, pierced, or blanked parts.

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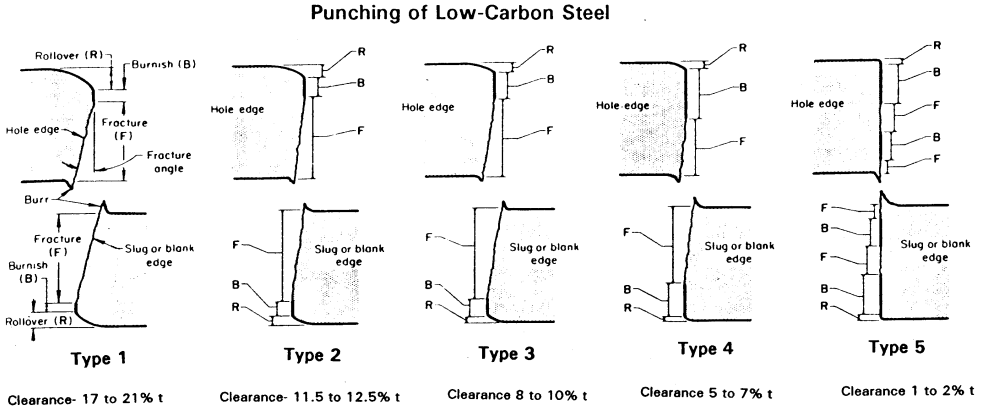

Edge Characteristic	Type 1	Type 2	Type 3	Type 4	Type 5
Fracture angle	14 to 16°	8 to 11°	7 to 11°	6 to 11°	.....
Rollover (1)	10 to 20% t	8 to 10% t	6 to 8% t	4 to 7% t	2 to 5% t
Burnish (1)	10 to 20% t (2)	15 to 25% t	25 to 40% t	35 to 55% t (3)	50 to 70% t (4)
Fracture	70 to 80% t	60 to 75% t	50 to 60% t	35 to 50% t (5)	25 to 45% t (6)
Burr	Large, tensile & part distortion	Normal, tensile only	Normal, tensile only	Medium, tensile + compressive (7)	Large, tensile + compressive (7)

Note: (1) Rollover plus burnish approx. equals punch penetration before fracture, (2) Burnish on edge of slug or blank may be small and irregular or absent, (3) With spotty secondary shear, (4) In two separate portions, alternating with fracture, (5) With rough surface, (6) In two separate portions, alternating with burnish, (7) Amount of compressive burr depends on die sharpness.

Figure 8.15 Edge characteristics.

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Figure 8.16 shows samples of typical slugs produced in the piercing or punching of hard copper (ETP 110, hard drawn). The figure clearly shows the effect of die clearance and the characteristic edges produced by the cutting (burnishing) and shear-fracture actions. (The cut or burnished section is indicated by *a* and the shear-fracture section by *b* in the figure.) These slugs are typical of type 1 and type 2 edges, as shown in Fig. 8.15.

Figure 8.17 gives punch-to-die clearances for piercing or blanking various metals and alloys to produce the five types of edge characteristics shown in Fig. 8.15. Clearances shown in Fig. 8.17 are based on data published on piercing by Danly Machine Corporation and on blanking by the American Society of Tool and Manufacturing Engineers (ASTME).

The tabular die-clearance data shown in Fig. 8.17 are given per side as a percentage of the stock thickness. For example, if we were punching stainless steel whose stock thickness was 0.050 in and we desired a type 3 edge, the total die clearance would be 0.05 × (0.09 to 0.11) × 2 = 0.009 to 0.011 in in total die clearance, or 0.0045 to 0.0055 in in clearance per side.

Another method that has been used for many years in industry for die clearances is outlined below.

Die Clearances per Side as a Percentage of Stock Thickness (Group Method)

Material group	Clearance per side, percent of stock thickness t
Group 1: 1100 and 5052 aluminum alloys (all tempers); 3003-0; etc.	4.5% t
Group 2: 2024 and 6061 aluminum alloys (all tempers); brass (all tempers); cold-rolled steel, soft; stainless steel, soft; copper, soft; BeCu, soft	6.0% t
Group 3: Cold-rolled steel, half hard; stainless steel, half hard and full hard; copper, hard	7.5% t
Group 4: Nonmetallic materials (general)	1.25% t

Note: Angular side clearance (one side) = 0.5 to 2 percent. Angular side clearance is cut below the die straight (see previous data for die-straight heights or thicknesses).

8.4.1 Calculation of punch dimensions

Punch dimensions may be estimated from the following: When the diameter of a pierced round hole is equal to the stock thickness, the

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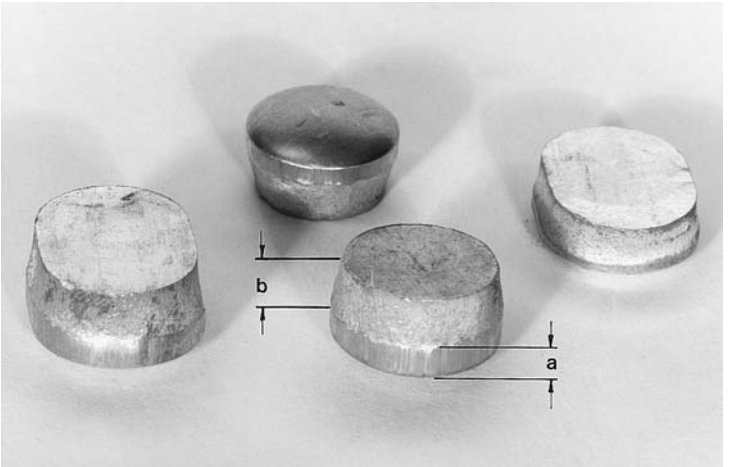

Figure 8.16 Typical die-punched slugs.

unit compressive stress on the punch is four times the unit shear stress on the cut area of the stock from the equation

$$1 = \frac{4S_s t}{S_c d}$$

where S_c = unit compressive stress on the punch, psi
S_s = unit shear stress on the stock, psi
t = stock thickness, in
d = diameter of punched hole, in

The diameters of most punched holes are greater than stock thickness, and a value for the ratio d/t of 1.1 is recommended. The maximum allowable length of a punch can be calculated from the following equation:

$$L = \frac{\pi d}{8}\sqrt{\frac{Ed}{S_s t}}$$

where d/t = 1.1 or higher
E = modulus of elasticity of the punch material, psi

Other terms were defined previously.

The punching of holes with diameters less than stock thickness is generally achieved by using high-compressive-strength tool steels, guided punches, greater than average die clearances, shear added

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Work Piece Material	Clearance per side, % of stock thickness *				
	Edge Type 1	Edge Type 2	Edge Type 3	Edge Type 4	Edge Type 5
Low-carbon steel	21 max	11.5-12.5	8-10	5-7	1-2
High-carbon steel	25 max	17-19	14-16	11-13	2.5-5
Stainless steel	23 max	12.5-13.5	9-11	3-5	1-2
Aluminum alloys: Up to 33,000 psi TS	17 max	8-10	6-8	2-4	0.5-1
Over 33,000 psi TS	20 max	12.5-14	9-10	5-6	0.5-1
Brass, annealed	21 max	8-10	6-8	2-3	0.5-1
Brass, half-hard	24 max	9-11	6-8	3-5	0.5-1.5
Phosphor bronze	25 max	12.5-13.5	10-12	3.5-5	1.5-2.5
Copper, annealed	25 max	8-9	5-7	2-4	0.5-1
Copper, half-hard	25 max	9-11	6-8	3-5	1-2
Lead	22 max	8-10	6.5-7.5	4-6	1.5-2.5
Magnesium alloys	16 max	5-7	3.5-4.5	1.5-2.5	0.5-1

NOTE: * Tabular data is clearance per side as % of stock thickness. Also, for clearances that produce edges of types 1, 2 and 3, it is usually necessary to use ejector punches or other devices to prevent the slug or blanked part from adhering to the punch.

Figure 8.17 Die clearances for piercing of various metals and alloys (for five types of edge characteristics as shown in Fig. 8.15).

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to the punch or dies, and prevention of stock slippage or movement during punching.

8.4.2 Standard die sets

Die sets are available from the major die supply manufacturers such as Danly and Dieco. Figures 8.18 and 8.19 show some of the most commonly used die sets that are available as stock items. In Fig. 8.18, the die sets are identified as follows:

a: Round series, back-post AS-31

b: Round series, center-post AS-32

c: Four-post series AS-37

d: Diagonal-post AS-35

e: Long, narrow series, two-post AS-41 and three-post AS-42

In Fig. 8.19, the die sets are identified as follows:

a: Four-post series AS-67

b: Two-post AS-63

c: Demountable two-post AS-39 or four-post AS-40

The top and bottom plates of a die set are called the *top shoe* and *bottom shoe,* respectively.

If a special size or configuration for a die set is not available commercially, the die set may be custom made by the die maker. In this case, the material and size of the top and bottom shoes and the optional shank are determined by the tool engineer. To complete the basic die set, guideposts and guide bushings must be selected. The guide bushings are available in plain or ball-bearing types.

8.4.3 Guide pins and guide bushings for die sets

When a die maker is building a custom die set, the guide pins and guide bushings are selected from commercially available types, which may be either plain or ball-bearing types. Guide pins and guide bushings are produced in various diameters and lengths, which must be determined by the design of the die set and the press used for the die operation.

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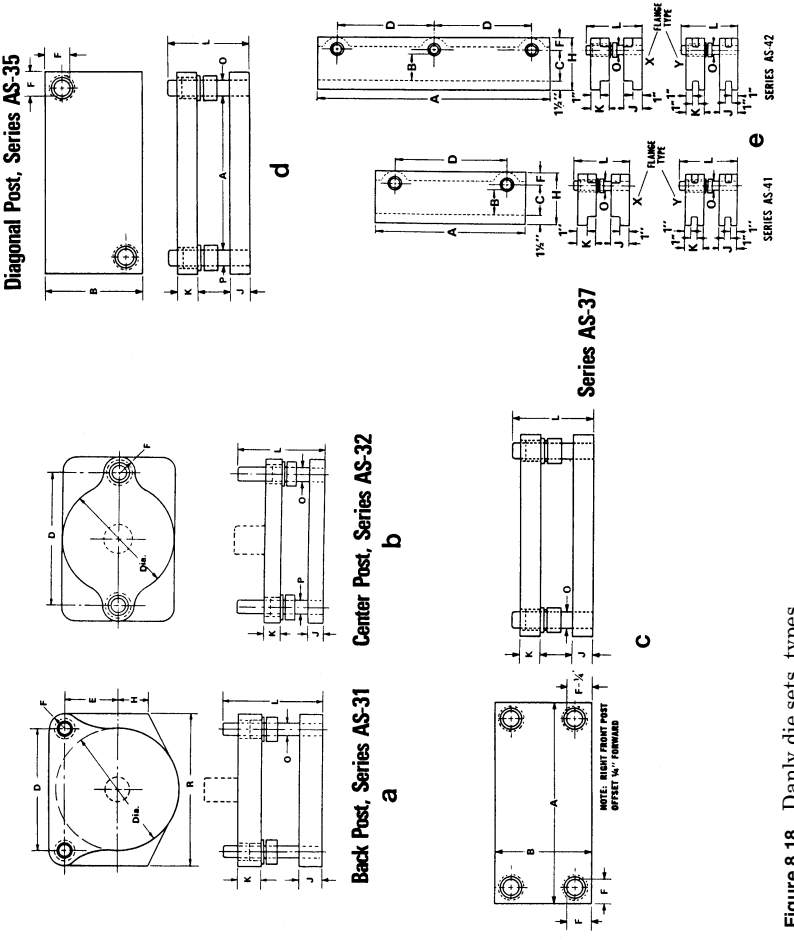

Figure 8.18 Danly die sets, types.

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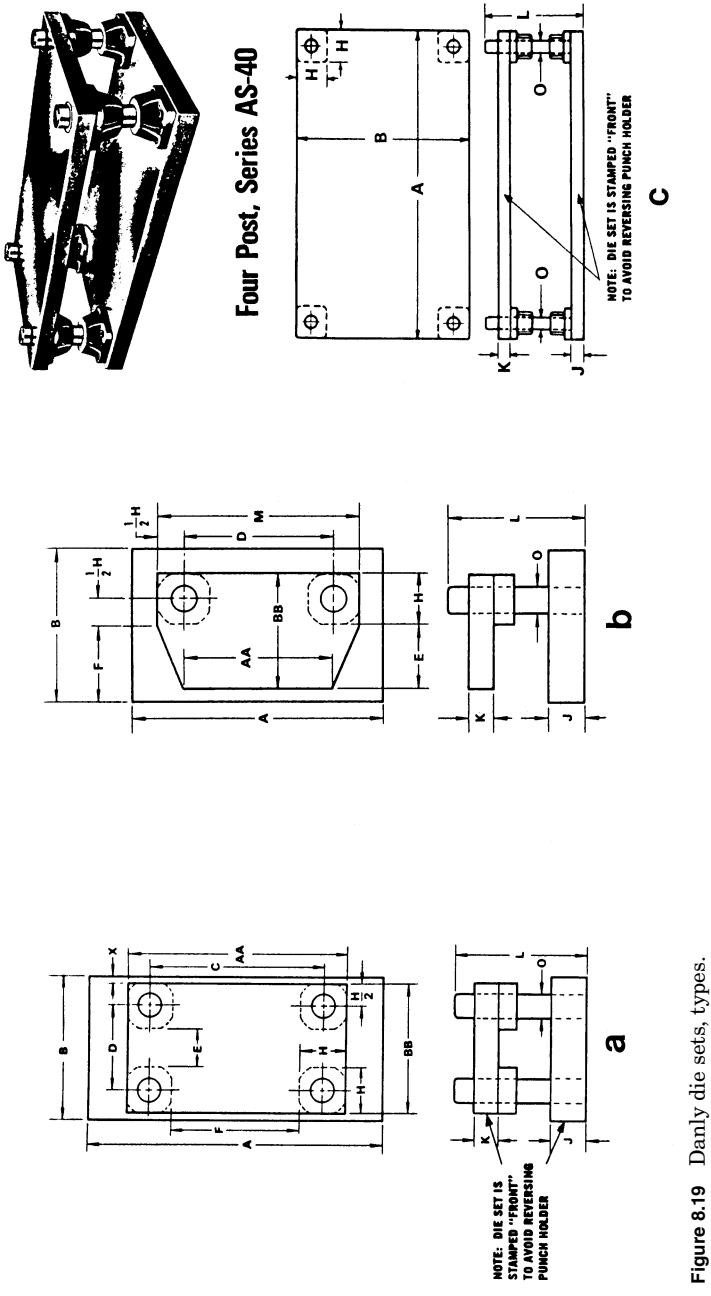
Four Post, Series AS-40
c
NOTE: DIE SET IS STAMPED "FRONT" TO AVOID REVERSING PUNCH HOLDER
b
a
NOTE: DIE SET IS STAMPED "FRONT" TO AVOID REVERSING PUNCH HOLDER

Figure 8.19 Danly die sets, types.

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Ball-bearing guide bushings are produced in three different types for different operating conditions. Figure 8.20 shows three types of ball-bearing guide bushings (*b*) and samples of typical die sets (*a*) that may use either plain or ball-bearing guide bushings. Selection of the correct type of ball-bearing guide bushing may be determined from the following descriptions:

Type I: Preloaded type. Recommended for use with high-production, long-life dies. All the balls remain in contact with the post and bushing in preloaded conditions throughout the press stroke.

Type II: Relieving type. Recommended when it is desirable that the ball cage does not leave the bushing at any time. Provides for safe operation and prevents foreign objects from falling into the bushing.

Type III: Disengaging type. Used where the ball cage can be permitted to leave the bushing with each stroke. This is the most economical type because of the short length, and it is used for general applications that require long press strokes.

These types of bushings should be ordered as complete sets (guidepost, ball cage, and bushing) to ensure proper fit of the components.

Important factors in designing and building any die set are

- Available stroke of the press
- Open height of the die set
- Minimum shut height (at depleted punch and die life)
- Maximum shut height (new punch and die sections)
- Dimension of the punch holder
- Dimension of the die holder
- Guidepost length
- Bushing length

Figure 8.21 shows the relations of these factors. The tool design engineer and die maker must determine the dimensions of all the factors listed and shown in this figure to produce the die correctly.

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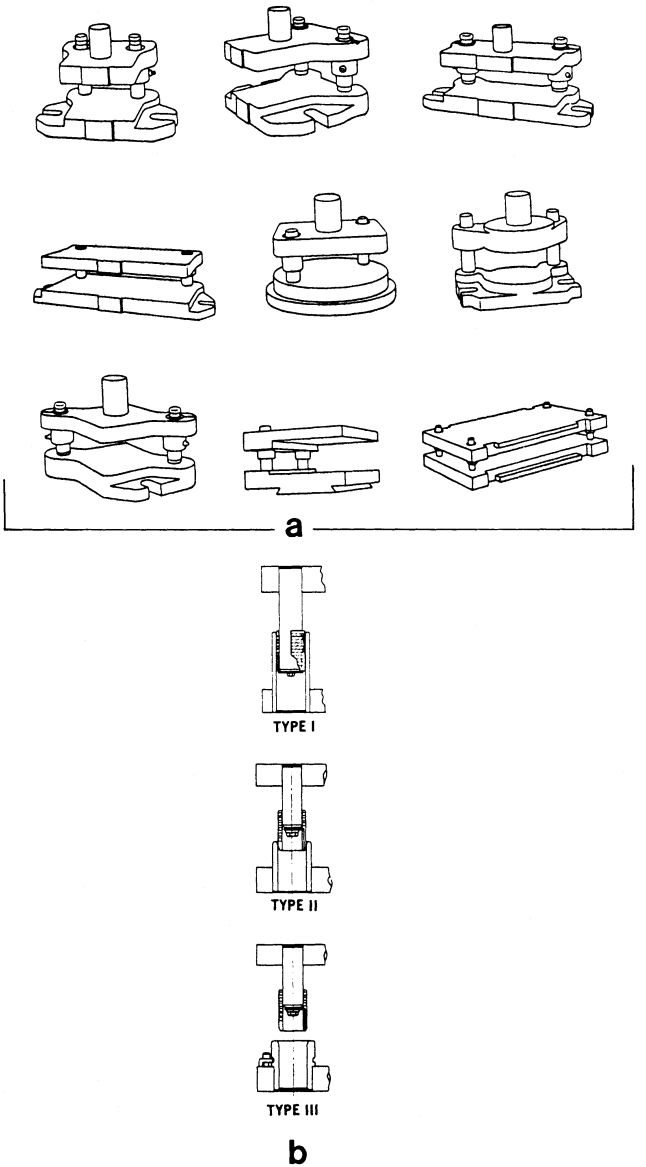

Figure 8.20 (*a*) Die sets. (*b*) Ball-bearing guide bushings.

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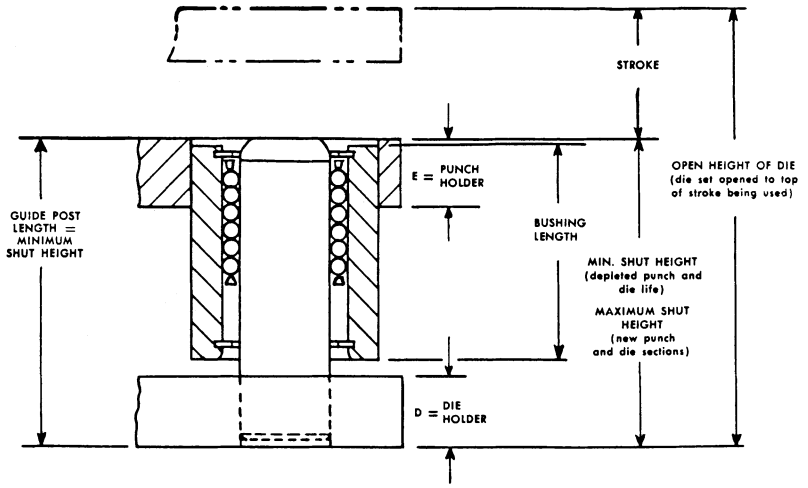
STROKE
E = PUNCH HOLDER
OPEN HEIGHT OF DIE (die set opened to top of stroke being used)
GUIDE POST LENGTH = MINIMUM SHUT HEIGHT
BUSHING LENGTH
MIN. SHUT HEIGHT (depleted punch and die life)
MAXIMUM SHUT HEIGHT (new punch and die sections)
D = DIE HOLDER

Figure 8.21 Die set variable characteristics.

8.5 Punching and Blanking Forces

8.5.1 Force required for punching or blanking

The simple equation for calculating the punching or blanking force P in pounds for a given material and thickness is given as

$$P = SLt \qquad \text{for any shape or aperture}$$

$$P = S\pi Dt \qquad \text{for round holes}$$

where P = force required to punch or blank, pounds force (lbf)
S = shear strength of material, psi (see Fig. 8.22)
L = sheared length, in
D = diameter of hole, in
t = thickness of material, in

8.5.2 Stripping forces

Stripping forces vary from 2.5 to 20 percent of the punching or blanking forces. A frequently used equation for determining the stripping forces is

$$F_s = 3500Lt$$

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where F_s = stripping force, lbf
L = perimeter of cut (sheared length), in
t = thickness of material, in

Note: This equation is approximate and may not be suitable for all conditions of punching and blanking owing to the many variables encountered in this type of metalworking.

8.5.3 Shear strengths of various materials

The shear strength (in pounds per square inch) of the material to be punched or blanked is required in order to calculate the force required to punch or blank any particular part. Figure 8.22 lists the average shear strengths of various materials, both metallic and nonmetallic. If you require the shear strength of a material that is not listed in Fig. 8.22 or elsewhere in this *Handbook*, then there are several Web sites such as *www.matweb.com* where shear strengths for a wide variety of materials may be obtained.

Manufacturers' standard gauges for steel sheets. The decimal equivalents of the American standard manufacturers' gauges for steel sheets is shown in Fig. 8.23. Sheet steels in the United States are purchased to these gauge equivalents, and tools and dies are designed for this standard gauging system.

8.6 Bending, Forming, and Progressive Die Operations and Data

Bending and forming dies are used to shape sheet metal parts by the action of bending or drawing the metal. Of concern to the die designer are allowable inside bend radii for various materials and gauges and permissible limits in the drawing or progressive forming of shapes with regular or irregular cross sections.

The die cavities used for forming metals may be ram EDM cut, as explained in an earlier section, or they may be cut using the CNC machining centers in profiling operations. The male portion of the die may be machined by various methods such as turning and milling on the modern CNC turning and machining centers or on engine lathes and manually controlled milling machines such as the Bridgeport machine.

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Material	Shear Strength, psi
Carbon Steels:	
SAE 1010 HR	21,500
SAE 1020 HR	32,000
SAE 1045 QT	55,000
SAE 1045 A	44,000
SAE 1095 QT	90,000
SAE 1095 A	63,000
SAE 1117 HR	32,000
Alloy Steels:	
SAE 4130 N	43,500
SAE 4130 T (150,000)	90,000
SAE 4140 N	66,500
SAE 3120 HT-D (800°F)	95,000
SAE 3140 HT-D (800°F)	130,000
SAE 3250 HT-D (800°F)	165,000
Stainless Steels:	
AISI 201	52,000
AISI 301	50,000
AISI 302	41,000
AISI 304	38,500
AISI 310	42,750
AISI 316	38,250
AISI 321	38,250
Cold rolled S/S strip (full hard)	
AISI 300 Series	112,000
Stainless Steels: Annealed	
AISI 410	33,750
AISI 416	33,750
AISI 440C	49,500
AISI 430	33,750
Monel Metal:	
70,000 UTS	42,900
110,000 UTS	65,500
K Monel:	
155,500 UTS	98,500
Nickel:	
68,000 UTS	52,300
121,000 UTS	75,300
Inconel Alloys:	
80,000 UTS	59,000
100,000 UTS	66,000
150,000 UTS	80,000
175,000 UTS	87,000
Copper and Alloys:	
CA 110 (ETP 110)	22,000-28,000
CA 210 (Guilding)	26,000-37,000
CA 220 (Bronze)	28,000-38,000
CA 230 (Red brass)	31,000-42,000
CA 260 (Cartridge brass)	33,000-44,000
CA 268 (Yellow brass)	33,000-43,000

Figure 8.22 Shear strength of metallic and nonmetallic materials, psi.

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Beryllium copper: Strip & sheet	
C 17200 (25)	34,200-54,000
C 17000 (165)	34,200-94,500
C 17510 (3)	24,750-67,500
C 17500 (10)	24,750-67,500
C 17410 (174) HT	58,500
Beryllium Nickel:	
UNS-N033 HT	123,750
Aluminum and Alloys:	
1100-O	9,000
1100-H18	13,000
2014-O	18,000
2014-T4, T451	38,000
2014-T6, T651	42,000
2024-O	18,000
2024-T3, T4, T351	41,000
3003-O	11,000
3003-H14	14,000
3003-H18	16,000
5052-O	18,000
5052-H32, H38	60,000-77,000
6061-O	12,000
6061-T4, T451	24,000
6061-T6, T651	30,000
7075-O	22,000
7075-T6, T651	48,000
7178-O	23,000
7178-T6, T651	53,300
Magnesium Alloys:	
Soft (annealed)	19,000
Hardened	28,500 max.
Titanium & Alloys:	
Pure	27,000-49,500
Typical alloys	45,000-77,000
Nonmetallics:	
Polyester-glass (GPO-1, 2 & 3)	12,000-17,000
Polycarbonate (Lexan)	6,000-10,000
Cycolac	4,400-7,400
ABS (Acrylonitrile Butadene Styrene)	1,500-4,000
Acetal (Delrin)	3,000-6,000
Acetate (Cellulose)	2,000-4,000
Epoxy-glass	4,000-10,000
Nylon	3,000-12,000
Phenolic resins (cloth)	26,000 (Hot-blanked)
Paper	3,500-6,400
Mica	10,000
Teflon, rigid (TFE)	1,500-3,000
Hard rubber	20,000
Polystyrene	10,000 max.
Asbestos board	5,000

Notes: For metallic materials- when the tabulated shear values are given in ranges, the shear values run from the annealed or soft condition to the hardest condition. Interpolate intermediate values between ranges. For nonmetallic materials- the shear value ranges are given from soft to hard grades or glass-filled grades.

A = annealed; HR = hot-rolled; N= normalized; T = tempered; HT-D = heat-treated and drawn (tempered); QT = quenched and tempered; UTS = ultimate tensile strength; HT = heat-treated.

Figure 8.22 (*Continued*)

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Progressive forming, bending, and blanking die design and die making are complex arts as well as technologies that require considerable skill, knowledge, and practical experience. This section will present some of the basic information and data important to die design and die making.

8.6.1 Typical forming and progressive dies and parts

Forming and bending dies may be made for very simple operations or for complex, multistaged operations used to blank, form, or bend complex sheet metal parts. Figure 8.24 shows a very simple forming die used to produce a raised indent on an electrical contact finger made of beryllium-copper alloy. In the figure, the small forming die is shown at the left, with samples of two finger contacts. Part usage per year did not justify the cost of producing a complex blanking and bending progressive die to produce these parts. Production of the parts shown required the following sequence of operations:

- Beryllium-copper strip was purchased in correct slit widths (soft condition).
- The two holes were strippit punched from the correct cut length of the part.
- The raised indent was then formed on the end of the part using the small forming die shown in the figure.
- The punched and indented part was then bent to shape on a small press brake.
- The part was then heat-treated to correct hardness (for spring action).
- The part was deburred by tumbling.
- Silver plating was then applied to the finished part.

Typical examples of punched, blanked, and formed sheet metal parts are shown in Figs. 8.25 and 8.26. Figure 8.25 shows a stainless steel sheet metal part that required spring action. The material selected for this application was AISI 301 spring-temper stainless steel. This part was preslit to proper width, shear-cut to length, punched, beaded for stiffness, and finally bent on the press brake.

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Standard Gage Number	Ounces/Ft^2	Lb/Ft^2	Thickness (Inches)
3	160	10.0000	0.2391
4	150	9.3750	0.2242
5	140	8.7500	0.2092
6	130	8.1250	0.1943
7	120	7.5000	0.1793
8	110	6.8750	0.1644
9	100	6.2500	0.1495
10	90	5.6250	0.1345
11	80	5.0000	0.1196
12	70	4.3750	0.1046
13	60	3.7500	0.0897
14	50	3.1250	0.0747
15	45	2.8125	0.0673
16	40	2.5000	0.0598
17	36	2.2500	0.0538
18	32	2.0000	0.0478
19	28	1.7500	0.0418
20	24	1.5000	0.0359
21	22	1.3750	0.0329
22	20	1.2500	0.0299
23	18	1.1250	0.0269
24	16	1.0000	0.0239
25	14	0.87500	0.0209
26	12	0.75000	0.0179
27	11	0.68750	0.0164
28	10	0.62500	0.0149
29	9	0.56250	0.0135
30	8	0.50000	0.0120
31	7	0.43750	0.0105
32	6.5	0.40625	0.0097
33	6	0.37500	0.0090
34	5.5	0.34375	0.0082
35	5	0.31250	0.0075
36	4.5	0.28125	0.0067
37	4.25	0.26562	0.0064
38	4	0.25000	0.0060

Note: Thickness equivalents are based on 0.0014945 in. per ounce per sq. ft.; 0.023912 in. per pound per sq. ft. (Reciprocal of 41.820 lb. per sq. ft. per inch thick); 3.443329 in. per lb. per sq. in.

Figure 8.23 Manufacturers' standard gauges for steel sheets.

Figure 8.26 shows a part made from no. 11 gauge low-carbon steel in a multistaged progressive die. This part required punching, blanking, bossing, and bending operations. The progressive die used for this type of part is complex and costly. The shear and forming marks are clearly evident on the surfaces of the part.

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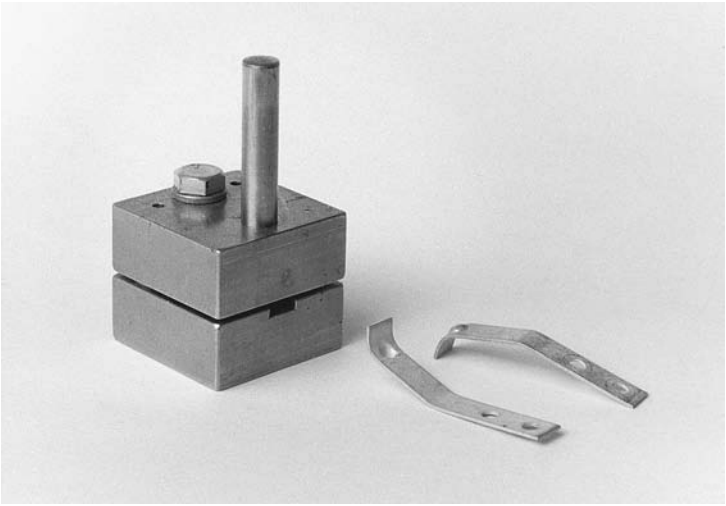

Figure 8.24 A small forming die and parts.

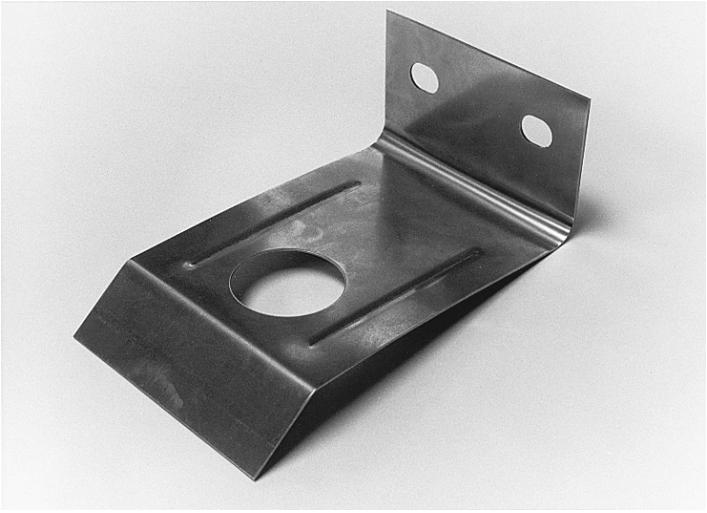

Figure 8.25 Die-punched stainless steel part.

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Figure 8.26 Die-punched mild-carbon-steel part.

A simple progressive punching and blanking die is shown in Fig. 8.27. The part strip and piece part are shown at the bottom of the figure; the dimensions are in millimeters. The punching, blanking, and part dropoff slot are shown in section *A*–*A*, progressing from right to left. A heavy-duty die set with an upper shank was used to make the die set shown in the figure.

A drawing die is shown in Fig. 8.28*a*, with the parts identified as follows:

1. Drawing punch
2. Drawing die block
3. Clamp ring (or holder)

A compound die for piercing and drawing is shown in Fig. 8.28*b*, with the parts identified as follows:

1. Shear punch and drawing-die block
2. Piercing die

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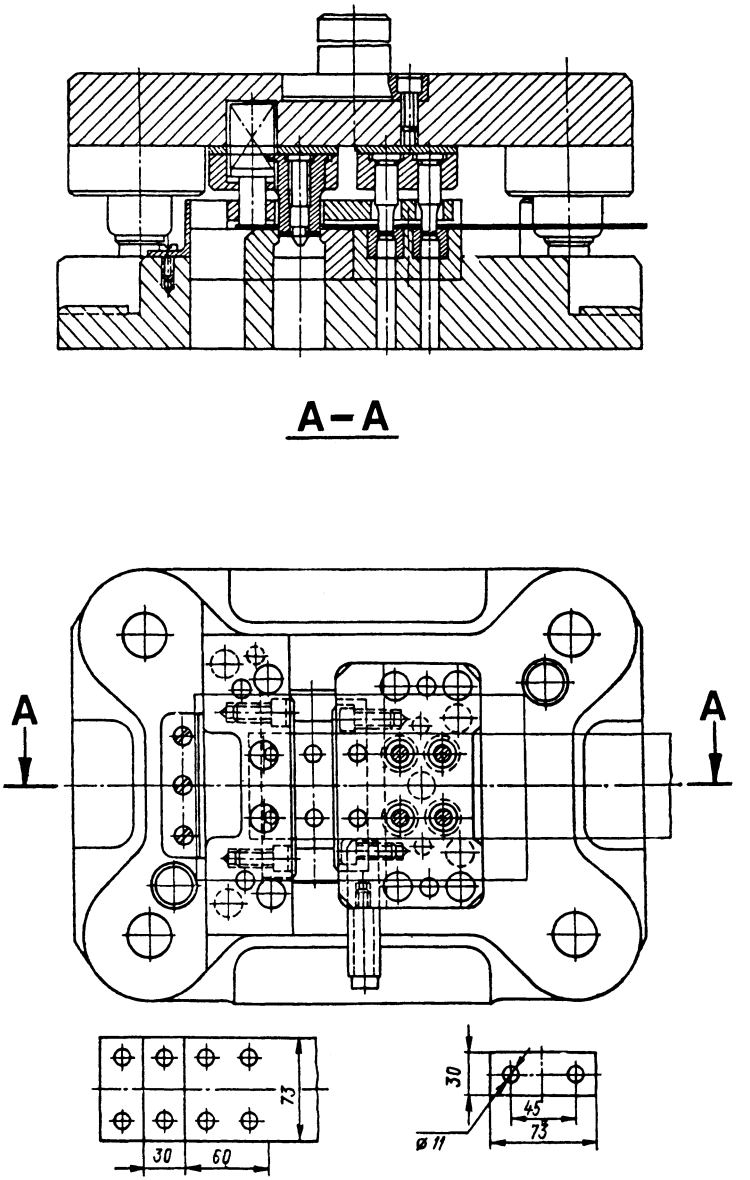

Figure 8.27 Progressive die with part samples.

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3. Shearing-die block
4. Clamping ring
5. Draw punch
6. Dimensioned finished part (millimeters)

See Sec. 8.6.5 for drawing and forming shapes and appropriate equations for drawing and forming calculations.

Methods for applying springs to die sets are shown in Fig. 8.29. Here, the springs are shown with methods of applying preload, with adjustment. Parts *c* and *e* of the figure illustrate the use of Belleville disk springs in place of the standard helical die springs. Helical die springs may be made with either round or rectangular spring wire, although the rectangular wire types are usually employed in American die-making practice because of their higher power-to-weight ratios.

8.6.2 Bend radii for various metals and alloys

The minimum bend radii allowed for forming metals and alloys are important factors in die design and die making. A bend radius that is too small for a particular metal and gauge may cause cracking or rupture of the part being formed. A radius that is too large may not meet the requirements of the part design. This is especially true when a hole is close to the edge or flange of a part and would interfere with the inside bend radius by running past the tangent point of the radius. This would cause "pulling" of the hole when the part is bent, with subsequent hole deformation.

Minimum bend radii for various metals and alloys are shown in Fig. 8.30. These bend radii are for cold bending the metals at room temperature (70°F) and at a 90° angle. These minimum bend radii are for an axis of the bend that is at 90° to the direction of rolling of the metal (commonly called *grain direction*). Larger bend radii are required when the bend axis is at 45° or parallel to the direction of rolling of the metal. The tables in Fig. 8.30 list the minimum bend radii as a multiple of the metal thickness. Thus a tabulated bend radius of 3.5 for 0.063-in-thick material indicates that the bend radius is actually equal to $3.5 \times 0.063 = 0.22$ in. In other words, we are multiplying the tabulated values times the material thickness to arrive at the minimum bend radius in inches.

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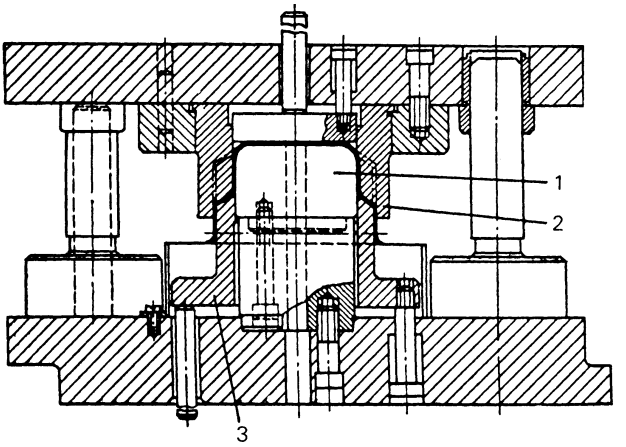
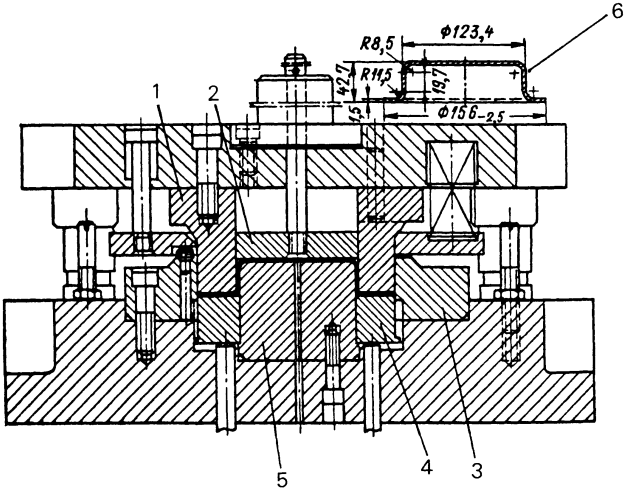


a



b

Figure 8.28 A complex drawing die.

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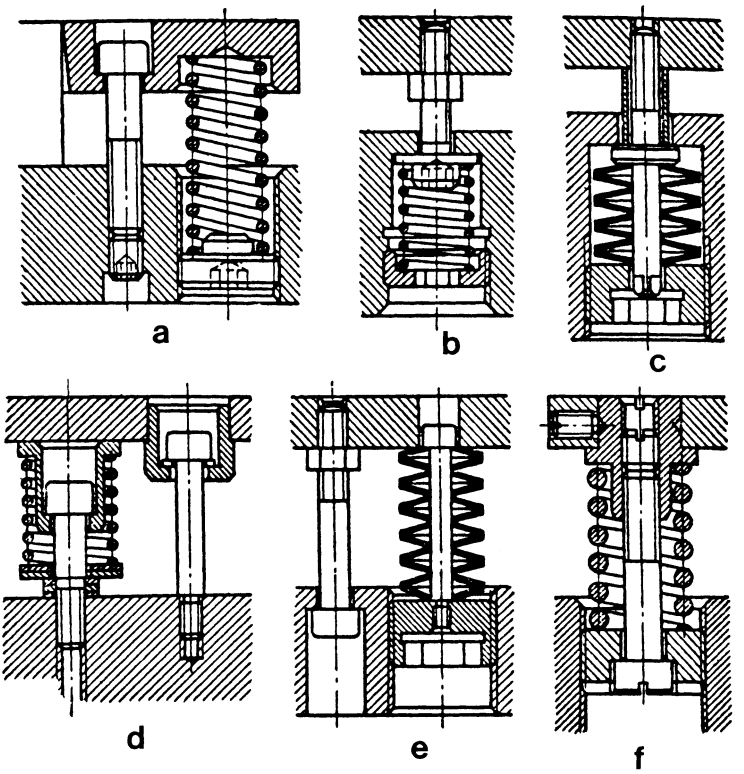

Figure 8.29 Die spring applications.

8.6.3 Springback

When a sheet of metal is bent, either in a die or on a press brake, the bent flange will tend to open to a larger angle when the bending pressure is removed (springback). In order to compensate for this characteristic, the flange usually is overbent by a certain number of degrees so that the metal will assume the correct angle of bend when the bending pressure is removed.

The harder the material, the greater is the amount of springback on the workpiece. Quarter-hard cold-rolled steel will exhibit approximately 1° to 2° of springback, half-hard has approximately 3° to 4°, hard steels have more than 5°, and annealed spring steels

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Minimum Bend Radii for Metals and Alloys- Given in Multiples of Material Thickness (inches)

Material		Thickness, inches 0.015	0.031	0.063	0.093	0.125	0.188	0.250
Carbon steels:								
SAE 1010		S	S	S	S	S	0.5	0.5
SAE 1020-1025		0.5	0.5	1.0	1.0	1.0	1.1	1.25
SAE 1070 & 1095		3.75	3.0	2.6	2.7	2.5	2.7	2.8
Alloy steels:								
SAE 4130 & 8630		0.5	2.0	1.5	1.7	1.5	1.7	1.9
Stainless steels:								
AISI 301, 302, 304 (A)		0.5					0.5	0.75
AISI 316 (A)		0.5					0.5	0.75
AISI 410, 430 (A)		1.0					1.0	1.25
AISI 301, 302, 304 (CR) ¼ H		0.5		0.5	1.0		1.0	1.25
AISI 316 ¼ H		1.0					1.0	1.25
AISI 301, 302, 304 ½ H		1.0					1.0	1.25
AISI 316 ½ H		2.0	2.0	3.0	2.0	2.0	2.0	2.5
AISI 301, 302, 304 H		2.0	2.0	1.5	1.5	1.5	1.5	1.5
Aluminum alloys:								
1100	O	0	0	0	0	0	0	0
	H12	0	0	0	0	0	3.0	6.0
	H14	0	0	0	0	0	3.0	6.0
	H1	0	0	2.0	3.0	4.0	8.0	16.0
	H18	1.0	2.0	4.0	6.0	8.0	16.0	24.0
2014 & Alclad	O	0	0	0	0	0	3.0	6.0
	T6	2.0	4.0	8.0	15.0	20.0	36.0	64.0
2024 & Alclad	O	0	0	0	0	0	3.0	6.0
	T3	2.0	4.0	8.0	15.0	20.0	30.0	48.0
3003, 5005,	O	0	0	0	0	0	0	0
5357, 5457	H12/H32	0	0	0	0	0	3.0	6.0
	H14/H34	0	0	0	1.0	2.0	4.0	8.0

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	H16/H36	0	1.0	3.0	5.0	6.0	12.0	24.0
	H18/H38	1.0	2.0	5.0	9.0	12.0	24.0	40.0
5050, 5052,	O	0	0	0	0	2.0	3.0	4.0
5652	H32	0	0	2.0	3.0	4.0	6.0	12.0
	H34	0	0	2.0	4.0	5.0	9.0	16.0
	H36	1.0	1.0	4.0	5.0	8.0	18.0	24.0
	H38	1.0	2.0	6.0	9.0	12.0	24.0	40.0
6061	O	0	0	0	0	2.0	3.0	4.0
	T6	1.0	2.0	4.0	6.0	9.0	18.0	28.0
7075 & Alclad	O	0	0	2.0	3.0	5.0	9.0	18.0
	T6	2.0	4.0	12.0	18.0	24.0	36.0	64.0
7178	O	0	0	2.0	3.0	5.0	9.0	18.0
	T6	2.0	4.0	12.0	21.0	28.0	42.0	80.0
Copper & alloys:								
ETP #110	soft	S	S	S	S	0.5	0.5	1.0
	hard	S	1.0	1.5	2.0	2.0	2.0	2.0
Alloy 210	¼ H	S	S	S	S	S	0.5	1.0
	½ H	S	S	S	S	S	1.0	1.5
	H	S	S	S	S	S	....	....
	EH	S	0.5	0.5	0.5	0.5	....	....
Alloy 260	¼ H	S	s	S	S	S	0.5	1.0
	½ H	S	S	S	0.3	0.3	....	....
	H	S	0.5	0.5	0.5	1.0	....	....
	EH	2.0	2.0	1.5	2.0	2.0	....	....
Alloy 353	¼ H	S	S	S	S	S	0.5	1.0
	½ H	S	0.5	0.5	0.7	0.3	....	....
	H	2.0	2.0	1.5	2.0	2.0	....	....
	EH	6.0	6.0	4.0	4.0	4.0	....	....
Magnesium sheet @ 70°F:								
	AZ31B-O (S.B.)	3.0						3.0
	AZ31B-O	5.5						5.5

Figure 8.30 Table of minimum bend radii.

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	AZ31B-H24	8.0					8.0
	HK31A-O	6.0					6.0
	HK31A-H24	13.0					13.0
	HM21A-T8	9.0					9.0
	HM21A-T81	10.0					10.0
	LA141A-O	3.0					3.0
	ZE10A-O	5.5					5.5
	ZE10A-H24	8.0					8.0
Titanium & alloys @ 70°F:							
	Pure (A)	3.0	3.0	3.0	3.5	3.5	3.5	3.5
	Ti-8Mn (A)	4.0	4.0	4.0	4.0	5.0	5.0	5.0
	Ti-5Al-2.5Sn (A)	5.5	5.5	5.5	5.5	6.0	6.0	6.0
	Ti-6Al-4V (A)	4.5	4.5	4.5	5.0	5.0	5.0	5.0
	Ti-6Al-4V (ST)	7.0						7.0
	Ti-6Al-6V-2Sn (A)	4.0						4.0
	Ti-13V-11Cr-3Al (A)	3.0	3.0	3.0	3.5	3.5	3.5	3.5
	Ti-4Al-3Mo-1V (A)	3.5	3.5	3.5	4.0	4.0	4.0	4.0
	Ti-4Al-3Mo-1V (ST)	5.5	5.5	5.5	6.0	6.0	6.0	6.0

Note: S = sharp bend; 0 = sharp bend; S.B. = special bending quality; A = annealed; ST = solution treated; H = hard; EH = extra hard; Magnesium sheet may be bent at temperatures to 800°F; titanium may be bent at temperatures to 1,000°F; on copper and alloys, direction of bending is at 90° to direction of rolling (bend radii must be increased 10-20% @ 45° and 25-35% parallel to direction of rolling). The tabulated values of the minimum bend radii are given in multiples of the material thickness. The values of the bend radii should be tested on a test specimen prior to die-design or production bending finished parts.

Figure 8.30 (*Continued*)

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may have as much as 15° to 20° of springback. The size of the bend radius on the part also influences the amount of springback on all materials.

The amount of springback will depend on the following factors:

- Type of material
- Hardness of the material and temper
- Radius of bend
- Gauge of the material

For practical die-making procedures, which must make allowances for springback of bent materials, trial pieces of material usually are bent to the desired radius in a press brake at 90°, and the actual springback is measured with a protractor. The 90° bend angle will open to a larger angle when the bending pressure is removed from the part.

Springback is not a problem when bending sheet metal parts or bar stock on a press brake because the brake operator can adjust the stroke of the press brake to form the correct angle. Once the stroke of the brake is determined and set, all parts made of the same material will bend to the correct angle, provided that the gauge or hardness of the material does not change during the operation.

To eliminate springback in forming-die designs, the punch or die may be shaped and angled to provide overbend of the part, thus eliminating springback.

8.6.4 Nonmetallic dies and materials

Plastic materials are used for some die and mold applications. Their use is not recommended unless the specifications for the plastic materials are within the physical limits of the application requirements. Figure 8.31 shows the range of properties available in cast unfilled plastics that may be used for tooling. Shrinkage during hardening, weathering, permanence, and dimensional stability must be considered when using plastic materials for tooling applications.

Phenolics are used for die models, stretch-form dies, duplicate masters, and semipermanent molds. The phenolics are limited to the casting applications and are brittle and react with various other materials.

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Properties of Major Tooling Plastics ♦

Property	Phenolic	Epoxy	Ethyl-cellulose
Specific gravity	1.30-1.32	1.11-1.23	1.09-1.17
Tensile strength, 10^3 psi	6-9	9-12	2-8
Modulus of elasticity, 10^6 psi	4.5	4.5	1.0-3.0
Compressive strength, 10^3 psi	12-15	15-18	10-35
Flexural strength, 10^3 psi	11-17	14-19	4-12
Impact (Izod) ft-lbs/in notch	0.25-0.40	0.45-1.7	2.0-8.0
Hardness, Rockwell	M93-120	M80-100	R50-115
Dimensional stability	Fair	Excellent	Good
Machinability	Excellent	Good	Good
Acid resistance	Good	Good	Poor
Alkali resistance	Poor	Excellent	Excellent
Solvent resistance	Fair	Excellent	Poor

Note: ♦ Per ASTM test methods.

Figure 8.31 Tooling plastics.

Epoxies are used for capped forming tools, metal-bonding tools, vacuum-forming tools, molding dies, and all plastic impact tools. Drawing dies having a metallic core and capped with a working face of epoxy are used in the appliance, automotive, and aerospace industries. Epoxy molding dies are being made to mold cycloaliphatic resins, which are two-part epoxy systems. Cycloaliphatic resins (epoxies) are now used widely for electrical insulators and support details and structures for live current-carrying parts in medium- and high-voltage applications in the switchgear industry. In effect, epoxy materials are molded in specially formulated epoxy molds. Special release agents are required to separate the cast epoxy part from the mold cavity. For long production runs, metal molds are made from tool steels. The plastic molding processes are discussed in Chap. 12, "Castings, Moldings, Extrusions, and Powder-Metal Technology."

Ethyl-cellulose compounds, which are thermoplastic materials, have been used for drop-hammer dies and other applications.

8.6.5 Drawing and forming shapes and equations

The diameter of the circular blank for producing simple drawn cylindrical parts may be approximated from

$$D = 1.13\sqrt{F} = 1.13\sqrt{\Sigma f}$$

where D = diameter of blank, in or mm
F = total area of part to be drawn, in^2 or mm^2
Σf = sum of the individual areas of the drawn part, in^2 or mm^2

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Equations for determining the blank diameters for many different drawn-part configurations are compiled in Fig. 8.32. These configurations are intended for material thickness and blank diameter ranges determined by the ratio $S/D \times 100 = 0.06$ to 2.0 using ductile metals or alloys in the soft or annealed condition (where S = material thickness, in or mm, and D = blank diameter, in or mm). The ratio of material thickness and blank diameter times 100 must fall within the range of 0.06 to 2.0 in order for the blank diameter D equations shown in Fig. 8.32 to be valid.

Example: A blank that is 5.00 in in diameter and 0.125 in thick would fall within the range of $0.125/5.00 \times 100 = 2.5$, which is *outside* the range of 0.06 to 2.0, as explained previously. A blank that is 4.00 in in diameter and 0.062 in thick would fall within the range of $0.062/4.00 \times 100 = 1.55$, which is *inside* the range of 0.06 to 2.0, making the equations valid for this combination of material thickness and blank diameter.

Figure 8.33 shows the step equations used to determine the drawn height at each step in the drawing process when we know the blank diameter, the drawing coefficients ($m_1, \ldots, m_n$), the workpiece diameter ($d_1, \ldots, d_n$), and the other variables indicated in the equations. Figures 8.34 through 8.39 give the drawing coefficients when we know the $S/D \times 100$ range, as well as approximations for the first drawing step height (h_1). The designations for the symbols shown in the equations in Fig. 8.33 are as follows:

D = diameter of the blank, in or mm
$d_1, d_2, \ldots, d_n$ = workpiece diameter for each operation, in or mm, proceeding from larger to smaller diameter as drawing steps increase
$a_1, a_2, \ldots, a_n$ = bevel dimensions for each operation (profile 3 only)
$m_1, m_2, \ldots, m_n$ = drawing coefficients for each operation (see Figs. 8.34 through 8.39)
$S, S_1, \ldots, S_n$ = blank thickness and wall thickness for each operation, in or mm
$d\phi$ = flange diameter, in or mm (for profile 6 only)
$r_1, r_2, \ldots, r_n$ = inside radius or corner radius for each operation, in or mm

The equations shown in Fig. 8.33 allow the tool designer to calculate the dimensions for the dies required in each step of the drawing operation. Some profile heights will require only one or two steps,

(Text continued on page 598.)

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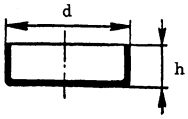
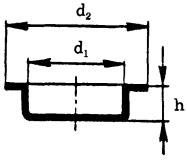
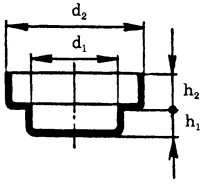
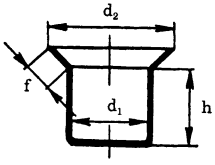
Figure	Drawn Profile	Diameter of Blank, D
1		$\sqrt{d^2 + 4dh}$
2		$\sqrt{d_2^2 + 4d_1h}$
3		$\sqrt{d_2^2 + 4\left(d_1h_1 + d_2h_2\right)}$
4		$\sqrt{d_1^2 + 4d_1h + 2f\left(d_1 + d_2\right)}$

Figure 8.32 Equations for determining blank diameters, drawing operations.

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Tooling, Die Making, Molds, Jigs, and Fixtures

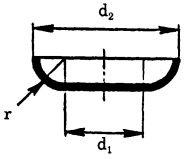
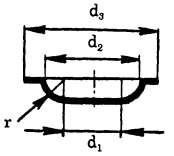
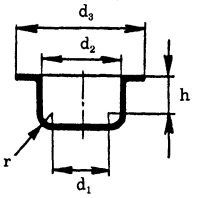
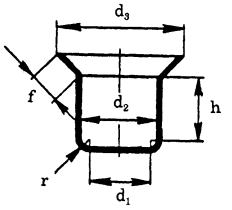
Figure	Drawn Profile	Diameter of Blank, D
5		$\sqrt{d_1^2 + 2\pi r d_1 + 8r^2}$
6		$\sqrt{d_1^2 + 2\pi r d_1 + 8r^2 + d_3^2 - d_2^2}$
7		$\sqrt{d_1^2 + 2\pi r d_1 + 8r^2 + 4d_2 h + d_3^2 - d_2^2}$
8		$\sqrt{d_1^2 + 2\pi r d_1 + 8r^2 + 4d_2 h + 2f(d_2 + d_3)}$

Figure 8.32 (*Continued*)

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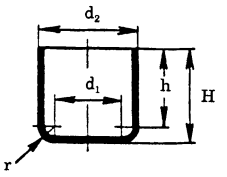
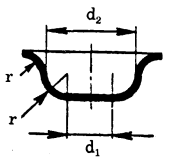
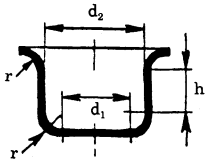
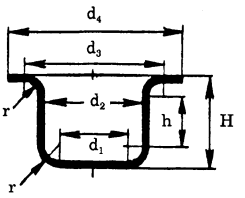
Figure	Drawn Profile	Diameter of Blank, D
9		$\sqrt{d_1^2 + 2\pi r d_1 + 8r^2 + 4d_2 h}$ or $\sqrt{d_2^2 + 4d_2 H - 1.72 r d_2 - 0.56 r^2}$ *
10		$\sqrt{d_1^2 + 2\pi r(d_1 + d_2) + 4\pi r^2}$
11		$\sqrt{d_1^2 + 2\pi r(d_1 + d_2) + 4d_2 h + 4\pi r^2}$
12		$\sqrt{d_1^2 + 4d_2 h + 2\pi r(d_1 + d_2) + 4\pi r^2 + d_1^2 - d_3^2}$ or $\sqrt{d_4^2 + 4d_2 H - 3.44 r d_2}$ *

Figure 8.32 (*Continued*)

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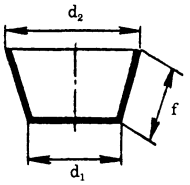
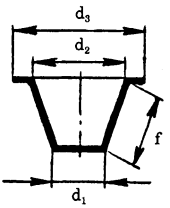
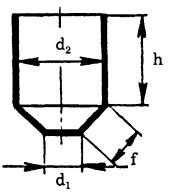
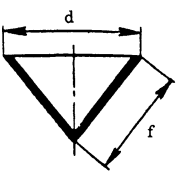
Figure	Drawn Profile	Diameter of Blank, D
13		$\sqrt{d_1^2 + 2f(d_1 + d_2)}$
14		$\sqrt{d_1^2 + 2f(d_1 + d_2) + d_3^2 - d_2^2}$
15		$\sqrt{d_1^2 + 2f(d_1 + d_2) + 4d_2h}$
16		$\sqrt{2df}$

Figure 8.32 (*Continued*)

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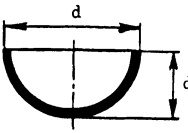
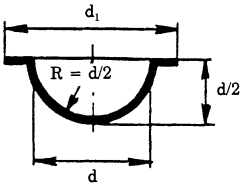
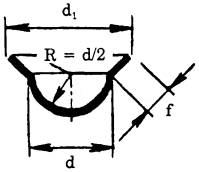
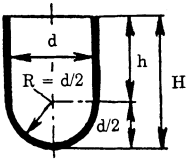
Figure	Drawn Profile	Diameter of Blank, D
17		$d\sqrt{2} = 1.414d$
18		$\sqrt{d^2 + d_1^2}$
19		$1.414\sqrt{d^2 + f(d + d_1)}$
20		$1.414\sqrt{d^2 + 2dh}$ or $2\sqrt{dH}$*

Figure 8.32 (*Continued*)

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Tooling, Die Making, Molds, Jigs, and Fixtures

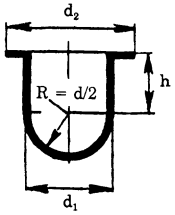
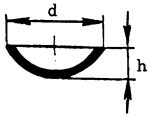
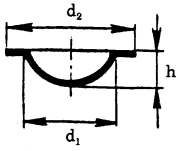
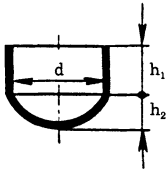
Figure	Drawn Profile	Diameter of Blank, D
21		$\sqrt{d_1^2 + d_2^2 + 4d_1h}$
22		$\sqrt{d^2 + 4h^2}$
23		$\sqrt{d_2^2 + 4h^2}$
24		$\sqrt{d^2 + 4\left(h_1^2 + dh_2\right)}$

Figure 8.32 (*Continued*)

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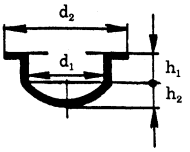
Figure	Drawn Profile	Diameter of Blank, D
25		$\sqrt{d_2^2 + 4\left(h_1^2 + d_1 h_2\right)}$

Note: Equations marked (*) were derived for using the full height of the part, H.

Figure 8.32 (*Continued*)

whereas others will require more than two successive drawing steps. The most critical variables used in the drawing operations are the drawing coefficients (m_1, m_2, . . . , m_n) and the first-step relative value of h/d for flanged parts. These values must be determined accurately using the tables in Figs. 8.34 through 8.39.

The drawing-process calculations for cylindrical parts consist of

1. Determination of the deformation limit (coefficients m_1, m_2, . . . , m_n).
2. Determination of the required number of steps.
3. Calculation of the drawn part dimensions for every step.

The deformation limits are determined by practical drawing coefficients m that were derived from experiments and proved by actual practice. The drawing coefficient for the first step is

$$m_1 = \frac{d_1}{D}$$

For the second step,

$$m_2 = \frac{d_2}{d_1}$$

Dimensions for the first step are

$$d_1 = m_1 D$$

(Text continued on page 603.)

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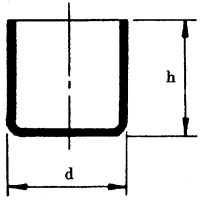
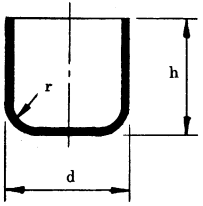
Figure	Workpiece Profile	Operation	Equation for Profile Height
1		Step 1	$h_1 = 0.25\left(\frac{D}{m_1} - d_1\right)$
		Step 2	$h_2 = 0.25\left(\frac{D}{m_1 m_2} - d_2\right)$
		Step n	$h_n = 0.25\left(\frac{D}{m_1 m_2 \cdots m_n} - d_n\right)$
2		Step 1	$h_1 = 0.25\left(\frac{D}{m_1} - d_1\right) + 0.43\frac{r_1}{d_1}\left(d_1 + 0.32\, r_1\right)$
		Step 2	$h_2 = 0.25\left(\frac{D}{m_1 m_2} - d_2\right) + 0.43\frac{r_2}{d_2}\left(d_2 + 0.32\, r_2\right)$
		Step n	$h_n = 0.25\left(\frac{D}{m_1 m_2 \cdots m_n} - d_n\right) + 0.43\frac{r_n}{d_n}\left(d_n + 0.32\, r_n\right)$

Figure 8.33 Equations for calculating the profile height h at each drawing step.

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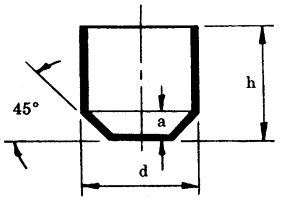
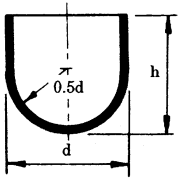
Figure	Workpiece Profile	Operation	Equation for Profile Height
3		Step 1	$h_1 = 0.25\left(\frac{D}{m_1} - d_1\right) + 0.57\frac{a_1}{d_1}\left(d_1 + 0.86\,a_1\right)$
		Step 2	$h_2 = 0.25\left(\frac{D}{m_1 m_2} - d_2\right) + 0.57\frac{a_2}{d_2}\left(d_2 + 0.86\,a_2\right)$
		Step n	$h_n = 0.25\left(\frac{D}{m_1 m_2 \ldots m_n} - d_n\right) + 0.57\frac{a_n}{d_n}\left(d_n + 0.86\,a_n\right)$
4		Step 1	$h_1 = 0.25\frac{D}{m_1}$
		Step 2	$h_2 = 0.25\frac{D}{m_1 m_2}$
		Step n	$h_n = 0.25\frac{D}{m_1 m_2 \ldots m_n}$

Figure 8.33 (*Continued*)

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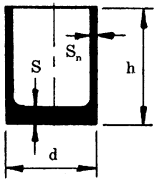
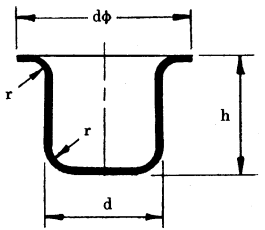
Figure	Workpiece Profile	Operation	Equation for Profile Height
5		Step 1	$h_1 = 0.25\left(\frac{D}{m_1} - d_1\right)\frac{S}{S_1} + S$
		Step 2	$h_2 = 0.25\left(\frac{D}{m_1 m_2} - d_2\right)\frac{S}{S_2} + S$
		Step n	$h_n = 0.25\left(\frac{D}{m_1 m_2 \cdots m_n} - d_n\right)\frac{S}{S_n} + S$
6		Step 1	$h_1 = 0.25\left(\frac{D}{m_1} - \frac{d\phi^2}{d_1} + 3.44\, r_1\right)$
		Step 2	$h_2 = 0.25\left(\frac{D}{m_1 m_2} - \frac{d\phi^2}{d_2} + 3.44\, r_2\right)$
		Step n	$h_n = 0.25\left(\frac{D}{m_1 m_2 \cdots m_n} - \frac{d\phi^2}{d_n} + 3.44\, r_n\right)$

Figure 8.33 (*Continued*)

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Tooling, Die Making, Molds, Jigs, and Fixtures

Coefficient Step	Coefficient Values for Relative Blank Thickness S/D x 100				
	2.0 - 1.5	1.5 - 1.0	1.0 - 0.5	0.5 - 0.2	0.2 - 0.06
m_1	0.46-0.50	0.50-0.53	0.53-0.56	0.56-0.58	0.58-0.60
m_2	0.70-0.72	0.72-0.74	0.74-0.76	0.76-0.78	0.78-0.80
m_3	0.72-0.74	0.74-0.76	0.76-0.78	0.78-0.80	0.80-0.82
m_4	0.74-0.76	0.76-0.78	0.78-0.80	0.80-0.82	0.82-0.84

Note: Tabulated values are the drawing coefficients. S = material thickness and D = blank diameter.

Figure 8.34 Drawing coefficients for cylindrical parts without flanges (profiles 1–5 of Fig. 8.33).

Relative Dia. of Flange, dϕ/d	Coefficient Values for Relative Blank Thickness S/D x 100				
	2.0 - 1.5	1.5 - 1.0	1.0 - 0.5	0.5 - 0.2	0.2 - 0.06
1.1	0.50	0.53	0.55	0.57	0.59
1.3	0.49	0.51	0.53	0.54	0.55
1.5	0.47	0.49	0.50	0.51	0.52
1.8	0.45	0.46	0.47	0.48	0.48
2.0	0.42	0.43	0.44	0.45	0.45
2.2	0.40	0.41	0.42	0.42	0.42
2.5	0.37	0.38	0.38	0.38	0.38
2.8	0.33	0.34	0.34	0.35	0.35

Note: Tabulated values are the drawing coefficients. S = material thickness and D = blank diameter.

Figure 8.35 Drawing coefficients for cylindrical parts with flanges (profile 6 of Fig. 8.33).

Relative Dia. of Flange dϕ/d	Value of (h/d) for Relative Blank Thickness S/D x 100				
	2.0 - 1.5	1.5 - 1.0	1.0 - 0.5	0.5 - 0.2	0.2 - 0.06
1.1	0.90-0.75	0.82-0.60	0.70-0.57	0.62-0.50	0.52-0.45
1.3	0.80-0.65	0.72-0.56	0.60-0.50	0.53-0.45	0.47-0.40
1.5	0.70-0.58	0.63-0.50	0.53-0.45	0.48-0.40	0.42-0.35
1.8	0.58-0.48	0.53-0.42	0.44-0.37	0.39-0.34	0.35-0.29
2.0	0.51-0.42	0.46-0.36	0.38-0.32	0.34-0.29	0.30-0.25
2.2	0.45-0.35	0.40-0.31	0.38-0.27	0.29-0.25	0.26-0.22
2.5	0.35-0.28	0.32-0.25	0.27-0.22	0.23-0.20	0.21-0.17
2.8	0.27-0.22	0.24-0.19	0.21-0.17	0.18-0.15	0.16-0.13

Note: Tabulated values are the values of h/d. (see profile 6 of Figure 9-29).
The larger tabulated values correspond to the larger radii r = (10-12)S for S/D x 100 = 2.0-1.5; r = (20-25)S for S/D x 100 = 0.2-0.06. The smaller tabulated values correspond to the smaller radii for bottom and flange where r = approx. (4-8)S. S is the material thickness and D is the blank diameter.

Figure 8.36 Approximate value of the first step relative depth (h/d) for cylindrical parts with flanges (profile 6 of Fig. 8.33)

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Blank Diameter (millimeters)	Height of Part (h_1) in 1st Step using Coefficients m_1						
	0.45	0.48	0.50	0.53	0.55	0.58	0.60 - (coefficients)
30	13	12	11	10	9.5	9	....
40	18	16	15	14	13	12	....
50	22	20	19	17	16	15	....
60	26	24	22	20	19	18	....
70	31	28	26	24	22	20	19
80	35	32	30	27	26	23	22
90	40	36	34	30	29	26	24
100	44	40	37	34	32	29	27
120	....	48	45	40	38	35	32
150	....	60	55	50	48	44	40
180	....	72	67	60	58	52	50
200	....	80	75	68	64	58	55

Note: Tabulated values are the height of the part in 1st drawing step, millimeters. (for profile 1, Fig.9-29)

Figure 8.37 Height of cylindrical part (h_1) for the listed drawing coefficients (profile 1 of Fig. 8.33).

Blank Diameter (millimeters)	Height of Part (h_1) in 1st Step using Coefficients m_1						
	0.45	0.48	0.50	0.53	0.55	0.59	0.60 - (coefficients)
30	14	13	12	11	10	10	....
40	19	17	16	15	14	13	....
50	23	21	20	17	16	15	....
60	28	26	24	22	21	20	....
70	33	30	28	26	24	22	21
80	37	34	32	29	28	25	24
90	42	38	36	32	32	29	27
100	47	43	40	37	35	32	30
120	....	52	49	44	42	39	36
150	....	65	60	55	53	49	45
180	....	77	72	65	63	57	55
200	....	88	81	74	70	64	61

Note:Tabulated values are the height of the part in 1st drawing step, millimeters. (for profile 2, Fig. 9-29)

Figure 8.38 Height of cylindrical part (h_1) for the listed drawing coefficients (profile 2 of Fig. 8.33).

For the second step,

$$D_2 = m_2 d_2$$

where D = blank diameter, in or mm
d = part diameter, in or mm
m = drawing coefficient

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Blank Diameter (millimeters)	Height of Part (h_1) in 1st Step using Coefficients m_1						
	0.48	0.50	0.53	0.55	0.58	0.60	0.62 - (coefficients)
120	53	50	45	43	40	37	....
150	66	61	56	52	50	46	....
180	79	74	67	65	59	57	....
200	88	83	76	72	66	63	58
250	110	103	95	90	83	78	73
300	132	122	114	108	98	92	86
350	154	144	134	126	116	108	102
400	176	166	152	144	132	123	115
450	198	184	172	162	148	140	130
500	220	205	190	180	165	155	145
550	242	226	210	198	182	172	160
600	264	244	228	216	200	185	173

Note: Tabulated values are the height of the part in 1st drawing step, millimeters. (for profile 3, Fig. 9-29)

Figure 8.39 Height of cylindrical part (h_1) for the listed drawing coefficients (profile 3 of Fig. 8.33)

In this way, knowing the coefficient *m,* we can determine the dimensions and number of steps.

Note: The dimensions used in Figs. 8.34 through 8.39 are given in millimeters. The drawing coefficients are dimensionless values (multipliers).

8.6.6 General rules for die stamping and forming operations

Some of the basic rules and dimensions for stamping and forming operations are shown in Figs. 8.40 through 8.44. The edge-distance recommendations shown in Fig. 8.40 for die-stamping metals are easy to apply during punching or stamping operations, but these distances (*A* and *B*) often are reduced when the gauge of the metal is below 0.020 in.

Figure 8.41 shows the common methods of relieving the bending stresses on intermediately flanged parts and parts with angle-notched ends. Figure 8.42 shows methods for minimum flanges and stiffening ribs on the heel of die-formed parts. Light-gauge sheet metal parts can be made quite strong with the addition of heel-applied stiffening webs. The load-carrying ability of thin-gauge sheet metal parts such as angles is greatly increased with the addition of these die-formed stiffening webs.

Figure 8.43 shows a 90° formed bead, which is common in thin sheet metal parts for obtaining stiffness without adding another

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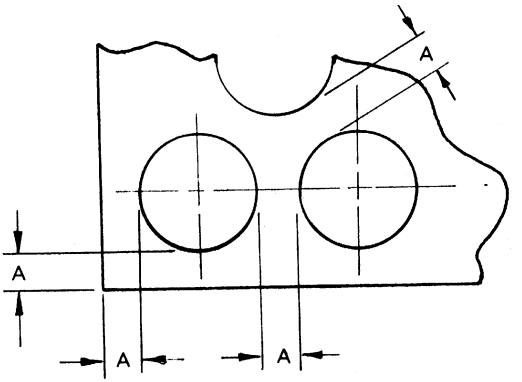
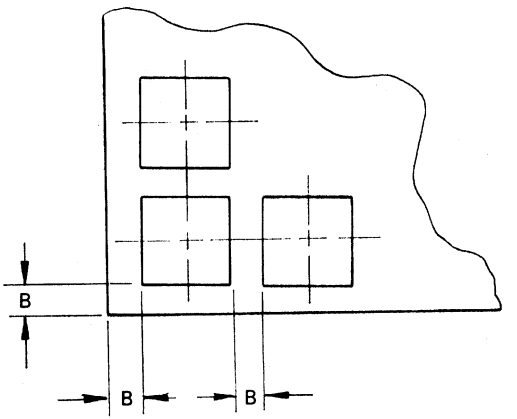


Material	Minimum Distance
Up to 0.062"	A = 0.12 Min.
Over 0.062"	A = 2 x Metal Thickness

a



Material	Minimum Distance
Up to 0.090"	B = 0.18"
Over 0.090"	B = 2 x Metal Thickness

b

Figure 8.40 (*a*) Minimum edge. (*b*) Minimum edge.

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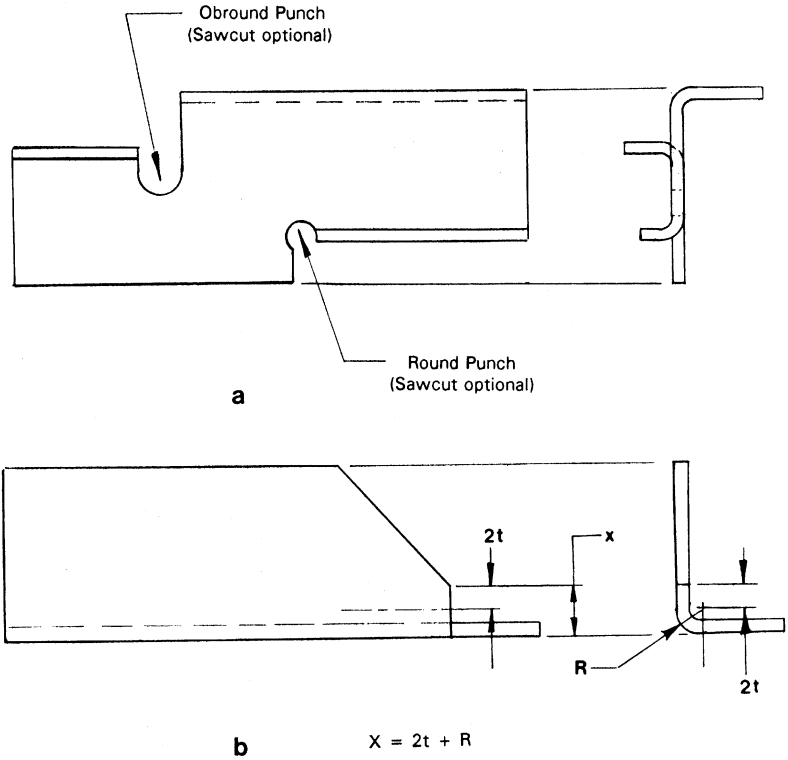

Figure 8.41 (*a*) Bend relief notches. (*b*) Notch limits.

member to the part. Automotive and aerospace sheet metal parts frequently contain stiffening beads and "lightening holes." See Chap. 9, "Sheet Metal Practices and Layout," for additional information on sheet metal bending and forming.

Figure 8.44 shows a 60° flat-bottomed bead. Such beads are normally larger than the 90° types shown in Fig. 8.43 and are used on large sheet metal parts.

Forces required for die bending. The force for die forming a flange (edge bending) may be calculated from

$$P = \frac{lt^2}{2W}(S_t) \qquad \text{(see Fig. 8.42)}$$

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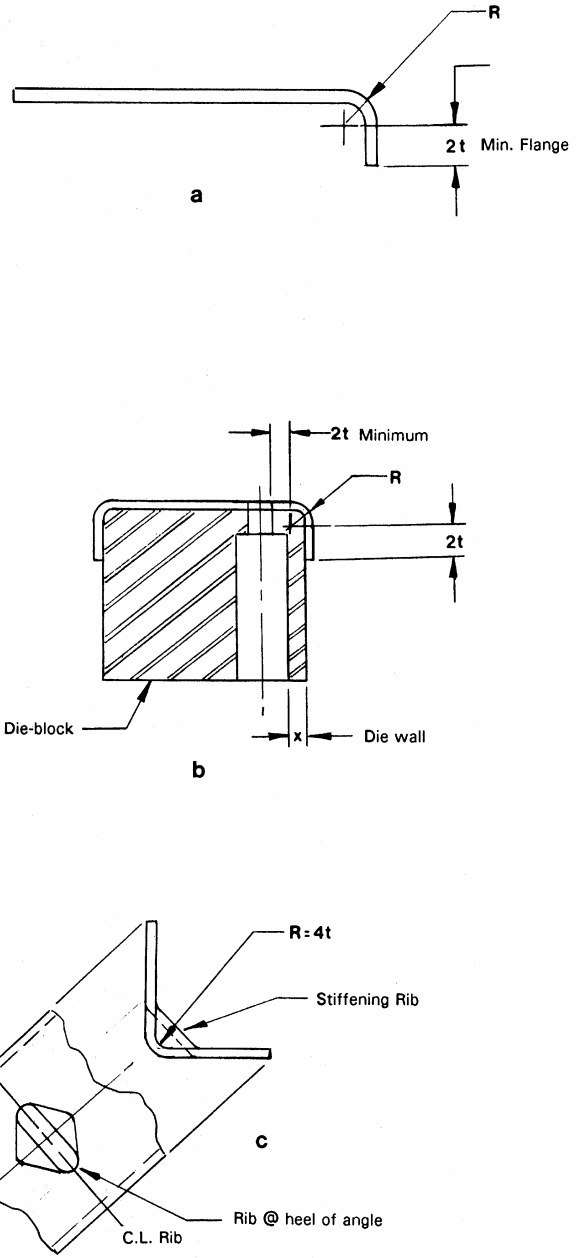

Figure 8.42 (*a*) Minimum flange. (*b*) Edge distance. (*c*) Rib.

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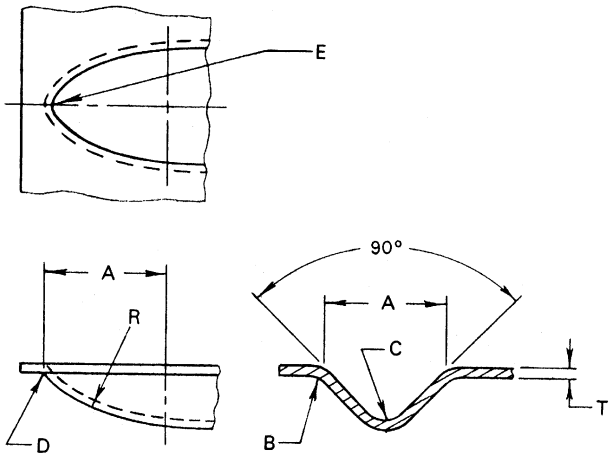

A	B (Radius)	C (Radius)	D (Radius)	E (Radius)
0.25	2T	2T	4T	T
0.38	2T	2T	4T	T
0.50	2T	2T	4T	2T
0.62	4T	4T	4T	2T
0.75	5T	5T	4T	3T
1.00	5T	5T	4T	3T

Figure 8.43 Stiffening beads.

The force required for V bending with a centrally located load may be calculated from

$$P = \frac{lt^2}{W}(S_t)$$

The force for bending channel and U bends may be calculated from

$$P = \frac{2lt^2}{W}(S_t)$$

where P = bending force, lbf
l = length of bend, in
t = material thickness, in
W = width of unsupported material, in
S_t = ultimate tensile strength of the material, psi

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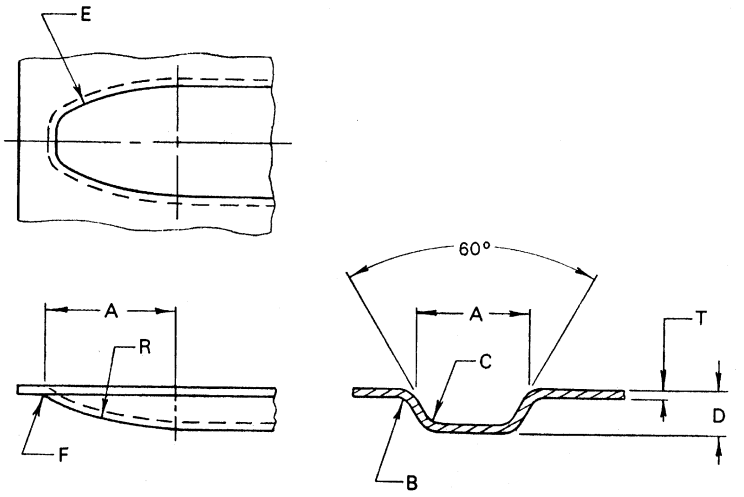

A	B (Radius)	C (Radius)	D	E (Radius)	F (Radius)
1.00	3T	2T	0.25	4T	4T
1.50	3T	2T	0.31	4T	4T

Figure 8.44 Stiffening beads.

8.7 Jigs and Fixtures

A *jig* is a tool that may be used as a guide to form (cut, grind, or file) the outline of a part. Jigs are also used with drill bushings to accurately drill and/or ream holes in a part. The jig is positioned accurately on the part to be drilled prior to drilling the holes. Stamped parts thus may be mass produced with additional drilled or reamed holes, making the parts accurate and interchangeable at the next assembly stage of manufacture. A drilling-guide tool is sometimes called a *drill fixture.* The terms *jig* and *fixture* sometimes are used interchangeably in industry when describing a drilling or reaming operation.

Different size drill bushings used in jigs and fixtures are shown in Fig. 8.45. The drill bushing is one of the most common parts used in tooling work. The drill bushing is available in different types and sizes to accommodate the different size drills and reamers. The bushing type may be plain cylindrical, flanged, press fit, or lock-in,

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according to the intended application. The correct definitions of drill bushing types are as follows:

- Headless press fit, type P
- Standard head, type H
- Slip/fixed, type SF

Figure 8.45 shows the plain bushing (P), flanged bushing (H), and lock-in bushing (SF). The lock-in or slip/fixed type of drill bushing is used when the production rates are high so that the bushing may be replaced easily as it wears during operation. Drill bushings are made of quality-grade tool steels with hardness ranges of Rockwell C 50 to C 60.

8.7.1 Tooling fixtures

A *tooling fixture* is a device used to accurately and efficiently aid the manufacturing processes. Fixtures are made in countless varieties and designs, including those for

- Assembly and subassembly
- Welding

Figure 8.45 Drill bushings.

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- Machining
- Machining pallets (quick-interchangeable fixtures)
- Heat treating
- Plating
- Wiring and cable harnesses

Tooling fixtures may weigh less than 1 oz or more than 100 tons. Large assembly fixtures, such as those used in the final assembly of aerospace vehicles or construction machinery, require the use of transits, optical/laser levels, and theodolites in order to position the critical parts accurately during construction of the fixture.

The properly designed tooling fixture has many requirements, such as

- Dimensional stability
- Dimensional accuracy
- Ease of manufacture
- Efficiency in use
- Practicality
- Cost-effectiveness
- Safety in operation

A typical small assembly fixture is shown in Fig. 8.46. The pneumatically actuated clamps used on this fixture are evident in the photograph. Holding clamps are important elements in the design of many fixtures. Section 8.8 will be useful to the tooling fixture designer and shows various clamp designs and calculation techniques for their application. Safety to manufacturing personnel is of prime importance when clamping devices are used on any tooling fixture, especially clamping devices that are pneumatically or hydraulically actuated.

Figure 8.47 shows an assembly fixture for pouring babbitt and epoxy potting compound into porcelain bushings used on a piece of electrical equipment. A brazed solid copper contact is first babbitted into place inside the porcelain bushing. While that is cooling, the epoxy potting compound is added to hold the porcelains to a polyester/glass mounting plate. This assembly fixture allows the assembly of two complete sets of bushings, comprised

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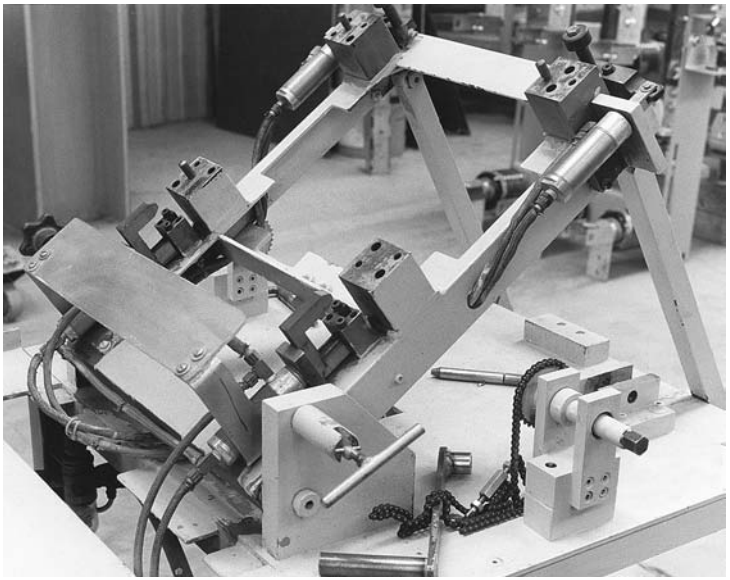

Figure 8.46 Pneumatic assembly fixture.

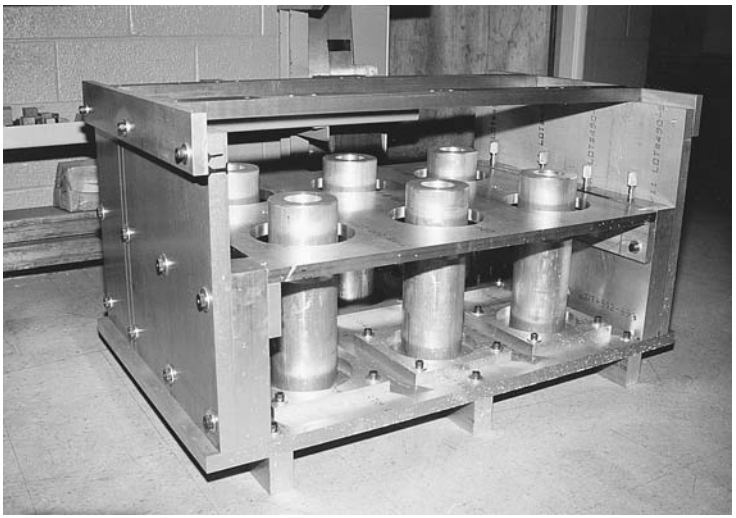

Figure 8.47 Compound assembly fixture for babbitting and epoxy-bonding a porcelain bushing assembly.

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of six contacts, six porcelain bushings, and two mounting plates. This completes the primary connection set for one breaker cell used on high-voltage switchgear. This newly designed assembly fixture allows the work to proceed at four times the original pace, thus saving time and money. Most of this assembly fixture is made from precision aluminum tooling plates. The sealing gaskets are held in place automatically by the fixture during the pouring processes. After the epoxy has set, the entire assembly is oven-heated at 350°F for 1 hour. After cooling, the completed primary electrical contact assemblies are easily removed from the fixture and assembled into the electrical equipment.

Figure 8.48 shows a drawing of a typical machining fixture that is actuated by a manual screw mechanism. The fixture drawing was generated by a CAD system and drawn on an automatic ink-pen plotter.

The design and application of tooling fixtures are as important to manufacturing processes as the design of the product that requires these fixtures for production, and in most cases, the fixtures are more difficult to design and have closer tolerances than the product itself.

8.7.2 Pallets

A *pallet* is a quickly removable indexed machining fixture that is used when maximum productivity of machined parts is required. In order for a palletizing system to be cost-effective, the cost of multiple pallets is weighed against the number of machined parts required for any particular job or production run.

The use of multiple pallets reduces machine "down time" drastically and makes the machined parts cost-effective when quantities are large enough to warrant a palletizing system.

In a palletized system, the machine operator loads multiple parts into different pallets while the machine tool is machining parts on a previously loaded pallet. All the pallets are pin indexed to fit the bed of the machine tool at a precise location relative to the zero position of the cutting tool or spindle centerline. In effect, the machine operator is using the normal idle time (while the CNC machine tool is operating) to load pallets (machining fixtures that hold multiple parts and which are quick changing).

A palletizing system is usually expensive to implement but is totally justified if it produces parts that are cost-effective when the cost to produce the parts meets or exceeds expected price goals and specifications.

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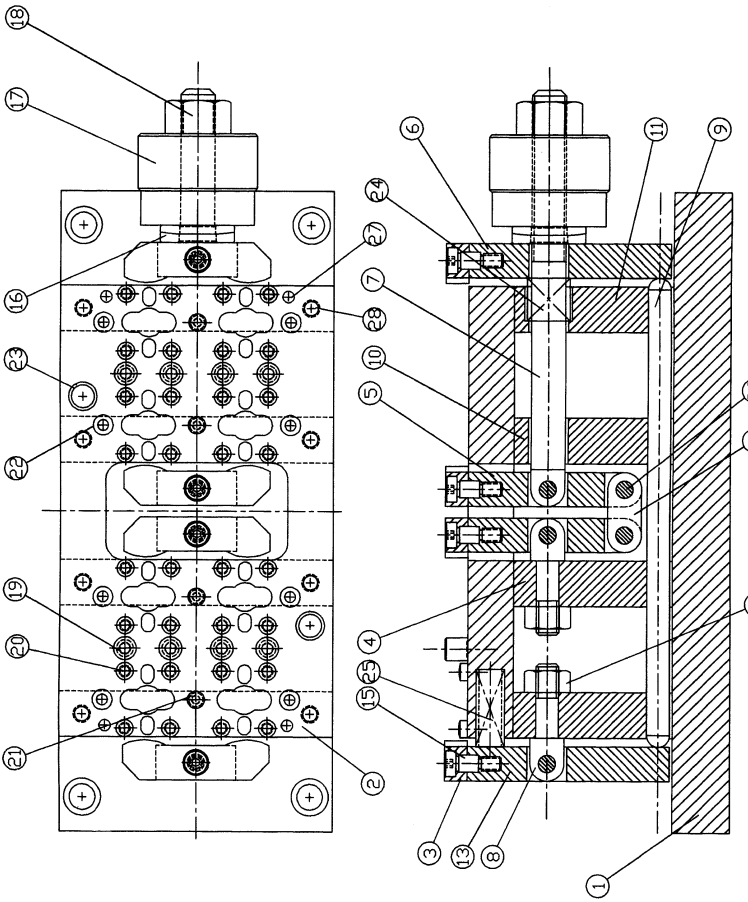

Figure 8.48 CAD drawing of a typical machining fixture.

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28	8	SHCS	9-1236-41	3/8x4 1/2	DANLY
27	2	DOWEL PIN	7-0832-1	ø1/4x2	DANLY
26	5	DOWEL PIN	7-1228-1	ø3/8x1 3/4	DANLY
25	1	SPRING	LC-072H-6		LEE
24	1	SPRING	LC-082M-3		LEE
23	2	BUSHING	10063	.5x.625	STEVENS
22	8	LOCATING PIN	CL-7A-SLP-3		CARR LANE
21	4	REST BUTTON	CL-14-RB	3/8x1/2	CARR LANE
20	32	LOCATOR BUTTON	CL-2-SLB	3/8x3/16	CARR LANE
19	8	REST BUTTON	CL-1-RB	1/2x1/2	CARR LANE
18	1	LOCK NUT	LN-750	3/4-10	VLIER
17	1	HOLLOW CYLINDER	CY2129-25	7415 LB	VLIER
16	1	SPHERICAL WASHER	CL-5-SW	3/4 DIA	CARR LANE
15	4	SHOULDER SCREW	CL-14-SS	1/2x.375	CARR LANE
14	2	NUT		3/8-13	
13	1	CLAMP LEVER	1018 STEEL	.75x1.75x4 7/16	
12	1	LINK	1045 STEEL	.75x.75x1.75	RC 38-40
11	1	SUPPORT BAR	1018 STEEL	1x3.5x6	
10	1	SUPPORT BAR	1018 STEEL	1x3.5x6	
9	1	PUSH ROD	O1 STEEL	ø1/2x10.25	RC 38-40
8	2	SWING BOLT	O1 STEEL	ø3/4x2.625	
7	1	PULL ROD	O1 STEEL	ø3/4x9 1/4	
6	1	CLAMP LEVER	1018 STEEL	.75x1.75x4 7/16	
5	2	CLAMP LEVER	1018 STEEL	.75x1.75x3 13/16	
4	2	SUPPORT BAR	1018 STEEL	1x3.5x6	
3	4	ADJUSTIBLE CLAMP	1045 STEEL	.5x.875x3.218	RC 40-45
2	1	TOP PLATE	1018 STEEL	1x6x9.875	
1	1	BASE PLATE	1018 STEEL	1 1/4x6x14	
POS	QTY	PART NAME	MATERIAL	DIMENSIONS	HARDNESS

Figure 8.48 (*Continued*)

8.8 Clamping Mechanisms and Calculation Procedures

Clamping mechanisms are an integral part of nearly all tooling fixtures. Countless numbers of clamping designs may be used by the tooling fixture designer and tool maker, but only the basic types are described in this section. With these basic clamp types, it is possible

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to design a vast number of different tools. Both manual and pneumatic/hydraulic clamping mechanisms are shown, together with the equations used to calculate each basic type.

The basic clamping mechanisms used by many tooling fixture designers are outlined in Fig. 8.49 (types 1 through 12). These basic clamping mechanisms also may be used for other mechanical design applications. Figure 8.50 shows a typical standard clamp set used on a milling machine.

Eccentric clamp, round. The eccentric clamp, such as that shown in Fig. 8.49 (type 12) is a fast-action clamp compared with threaded clamps, but threaded clamps have higher clamping forces. The eccentric clamp usually develops clamping forces that are 10 to 15 times higher than the force applied to the handle.

The ratio of the handle length to the eccentric radius normally does not exceed 5 to 6, whereas for a swinging clamp or strap clamp (threaded clamps), the ratio of the handle length to the thread pitch diameter is 12 to 15. The round eccentrics are relatively cheap and have a wide range of applications in tooling.

The angle α in Fig. 8.49 (type 12) is the rising angle of the round eccentric clamp. Because this angle changes with rotation of the eccentric, the clamping force is not proportional at all handle rotation angles. The clamping stroke of the round eccentric at 90° of its handle rotation equals the roller eccentricity e. The machining allowance for the clamped part or blank x must be less than the eccentricity e. To provide secure clamping, eccentricity $e \geq x$ to $1.5x$ is suggested.

The round eccentric clamp is supposed to have a self-holding characteristic to prevent loosening in operation. This property is gained by choosing the correct ratio of the roller diameter D to the eccentricity e. The holding ability depends on the coefficient of static friction. In design practice, the coefficient of friction f normally would be 0.1 to 0.15, and the self-holding quality is maintained when f exceeds $\tan \alpha$.

The equation for determining the clamping force P is

$$P = Ql \frac{l}{[\tan(\alpha + \phi_1)\tan\phi_2]r}$$

Then the necessary handle torque ($M = Pl$) is

$$M = P[\tan(\alpha + \phi_1) + \tan\phi_2]r$$

(Text continued on page 623.)

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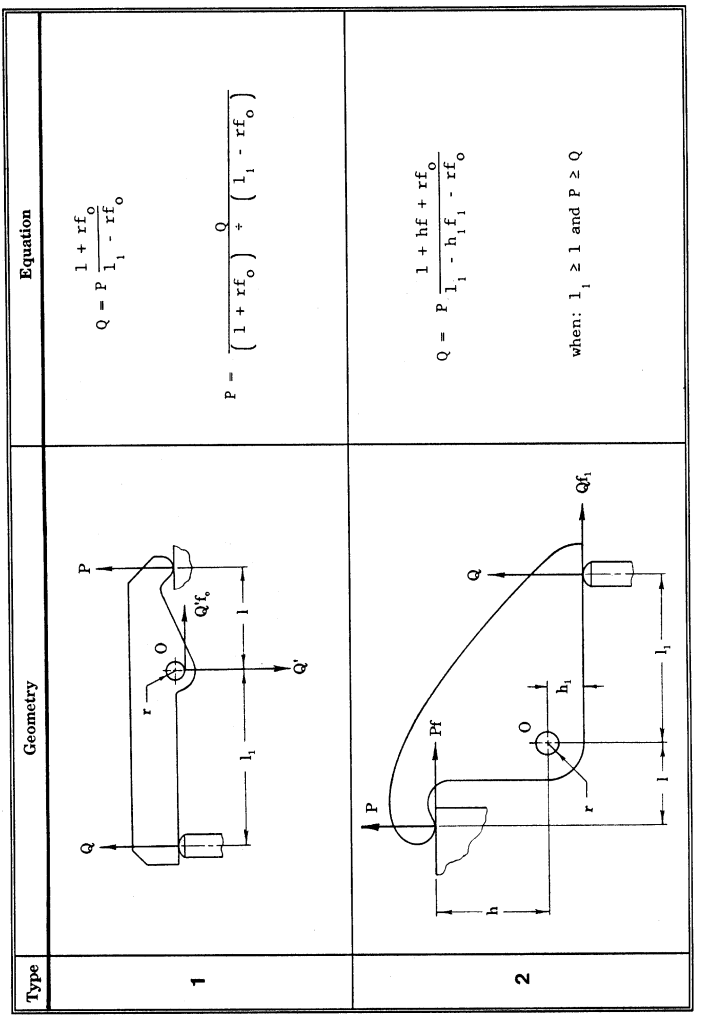

Figure 8.49 Basic clamping mechanisms (lever, cam, screw, pneumatic, and hydraulic).

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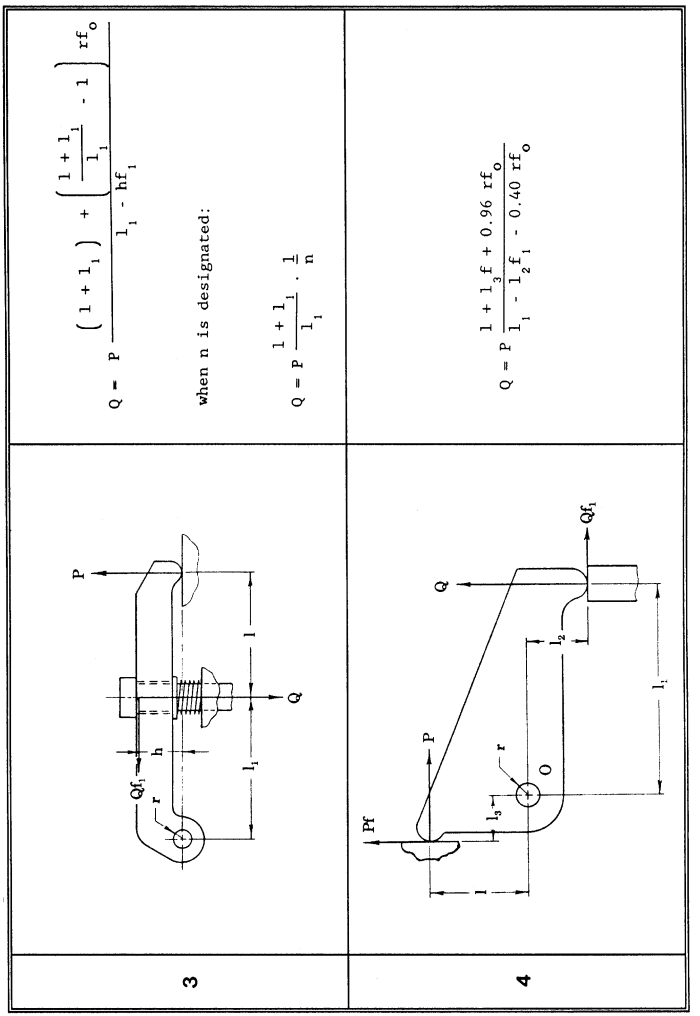

$$Q = P \frac{\left(1 + l_1\right) + \left(\frac{1 + l_1}{l_1} - 1\right) rf_o}{l_1 - hf_1}$$

$$Q = P \frac{1 + l_1}{l_1} \cdot \frac{1}{n}$$

$$Q = P \frac{1 + l_3 f + 0.96\ rf_o}{l_1 - l_2 f_1 - 0.40\ rf_o}$$

Figure 8.49 *(Continued)*

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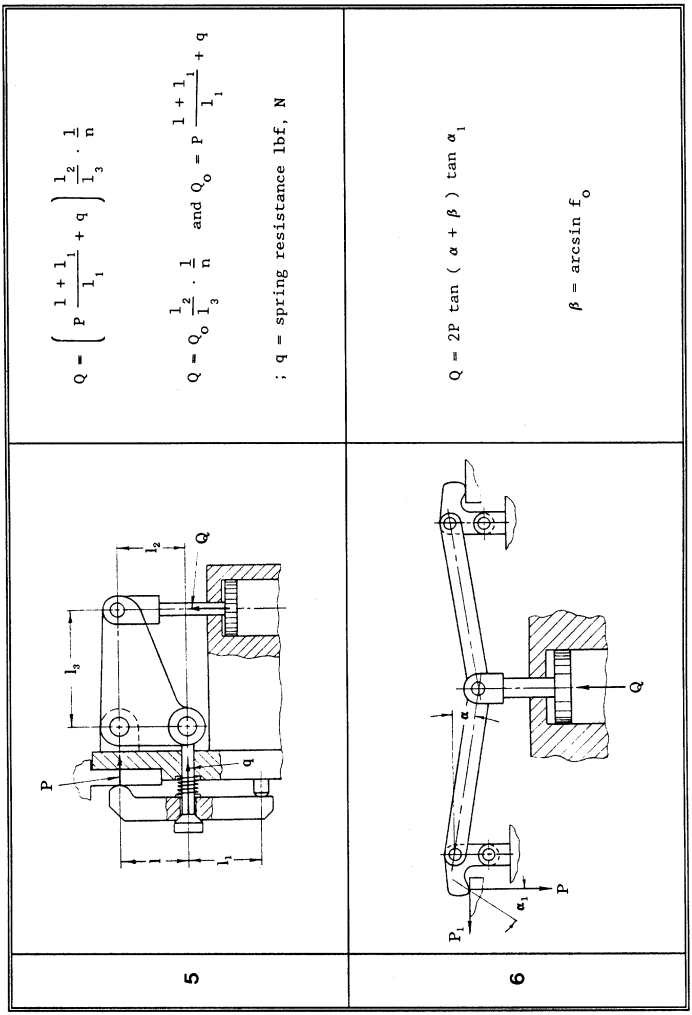

Figure 8.49 (*Continued*)

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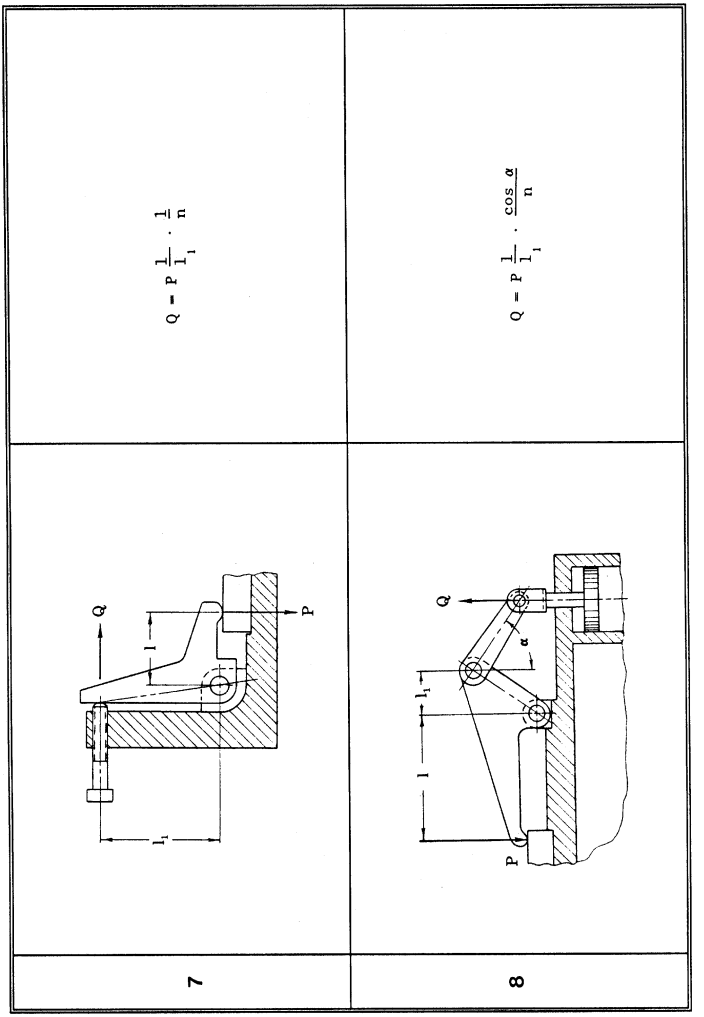

Figure 8.49 *(Continued)*

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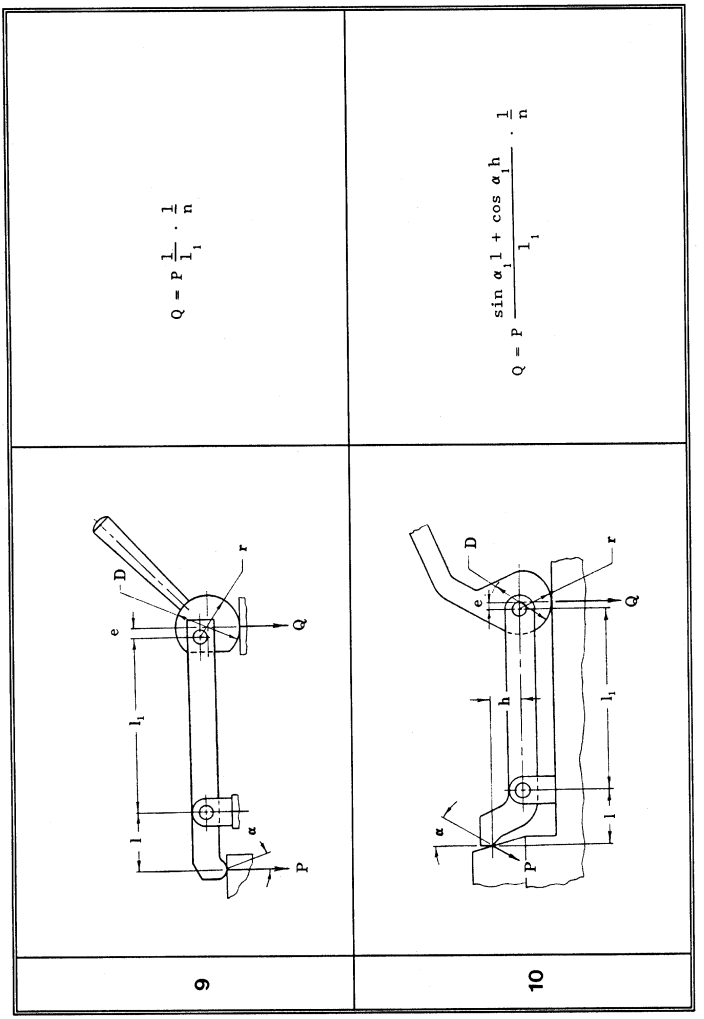

Figure 8.49 *(Continued)*

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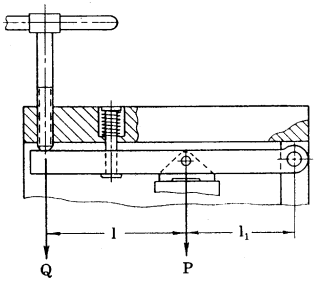
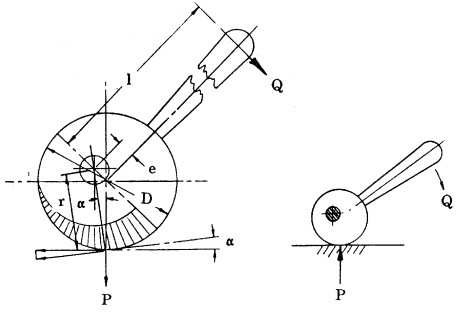
11		$Q = P \frac{l}{l + l_1} \cdot \frac{1}{n}$
12		See Text

NOTE: f_o = coefficient of friction (axels and pivot pins) = 0.1 to 0.15 ; f = coefficient of friction of clamped surface = tan ϕ ; ϕ_1 = arctan f ; n = efficiency coefficient, 0.98 to 0.84, (determined by frictional losses in pivots and bearings, 0.98 for the best bearings through 0.84 for no bearings, (in order to avoid the use of complex, lengthy equations, the value of "n" can be taken as a mean between the limits shown) ; q = spring resistance or force, pounds or Newtons, (lbf or N).

Figure 8.49 (*Continued*)

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Tooling, Die Making, Molds, Jigs, and Fixtures

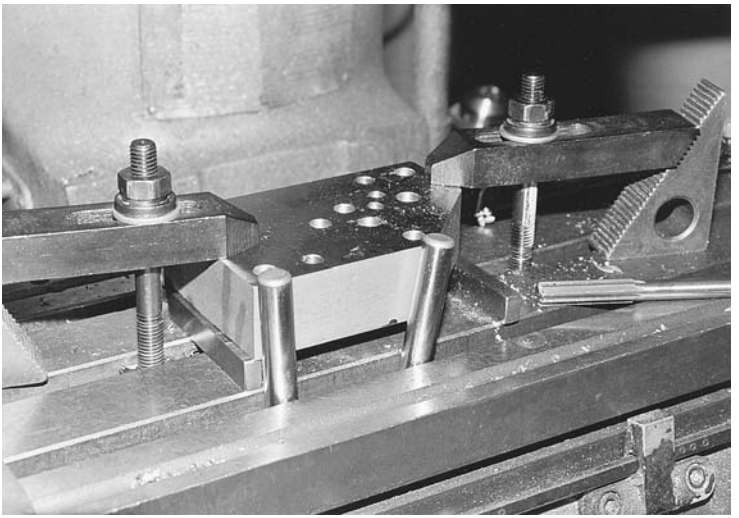

Figure 8.50 Standard basic machining clamps for milling operations.

where r = distance from pivot point to contact point of the eccentric and the machined part surface, in or mm
α = rotation angle of the eccentric at clamping (reference only)
$\tan \phi_1$ = friction coefficient at the clamping point
$\tan \phi_2$ = friction coefficient in the pivot axle
l = handle length, in or mm
Q = force applied to handle, lbf or newtons
D = diameter of eccentric blank or disk, in or mm
P = clamping force, lbf or newtons

Note: $\tan(\alpha + \phi_1) \approx 0.2$ and $\tan \phi_2 \approx 0.05$ in actual practice. See Fig. 8.51 for listed clamping forces for the eccentric clamp shown in Fig. 8.49 (type 12).

The cam lock. Another clamping device that may be used instead of the eccentric clamp is the standard cam lock. In this type of clamping device, the clamping action is more uniform than in the round eccentric, although it is more difficult to manufacture. A true camming action is produced with this type of clamping device. The method for producing the cam geometry is shown in Fig. 8.52. The layout shown is for a cam surface generated in 90° of rotation

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D mm (inches)	Clamping Force, P (Newtons)						
	490	735	980	1225	1470	1715	1960
40 (1.58")	2.65	3.97	5.40	6.67	8.00	9.37	10.64
50 (1.98")	3.34	5.00	6.67	8.39	10.01	11.77	13.68
60 (2.36")	4.02	6.03	8.00	10.01	11.97	14.03	16.48
70 (2.76")	4.71	7.06	9.42	11.77	14.08	16.48	18.79

NOTE: Tabulated values are torques (Newton-meters).
To convert clamping forces in Newtons to pounds-force, multiply table values by 0.2248, (i.e. 1960 N = 1960 x 0.2248 = 441 lbf).
To convert tabulated torques in Newton-meters to pounds-feet, multiply values by 0.7376, (i.e. 18.79 N-m = 18.79 x 0.7376 = 13.9 lbs-ft).

Figure 8.51 Torque values for listed clamping forces—eccentric clamps (type 12, Fig. 8.49).

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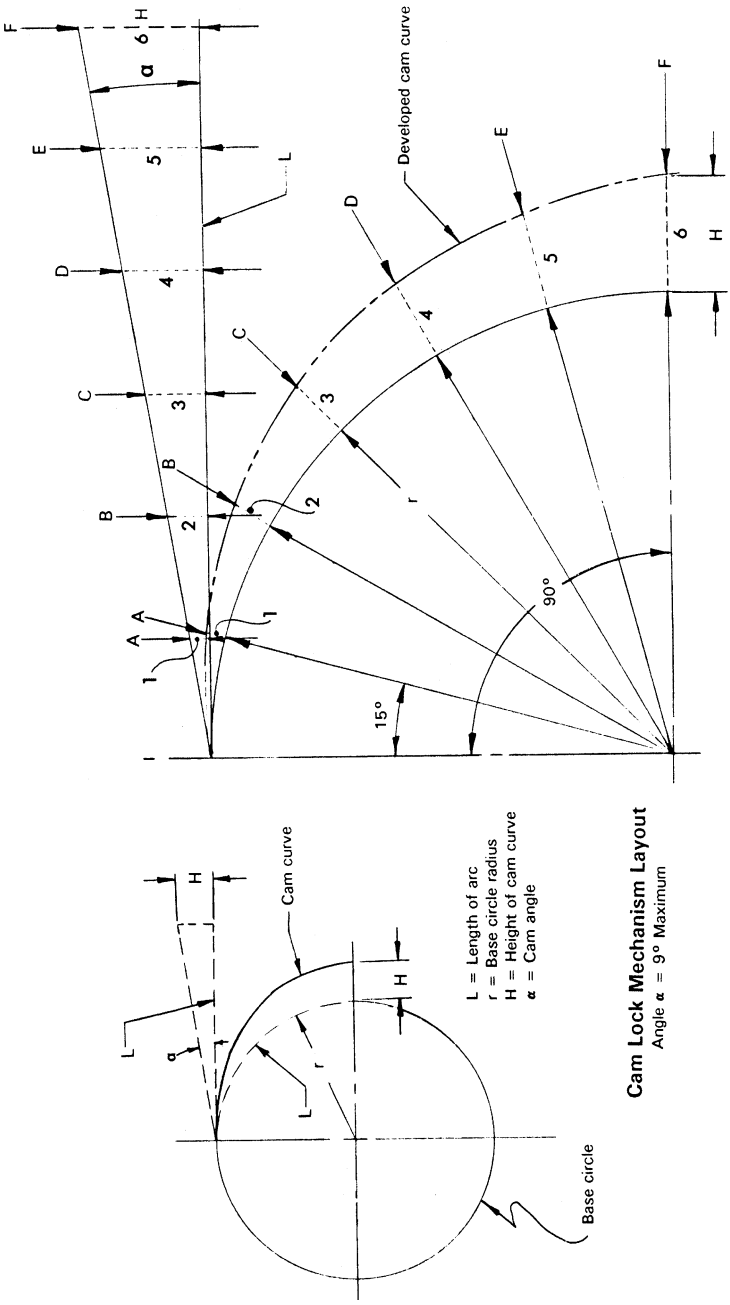

Figure 8.52 Determining cam geometry.

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of the device, which is the general application. Note that the cam angle should not exceed 9° in order for the clamp to function properly and be self-holding. The cam wear surface should be hardened to approximately Rockwell C 30 to C 50 or according to the application and the hardness of the materials that are being clamped. The cam geometry may be developed using CAD, and the program for machining the cam lock may be loaded into the CNC of a wire EDM machine.

8.9 Molds

Tooling practice also includes the design and manufacture of various types of molds. Molds are made for casting metals and alloys and for injection and compression molding plastics. Injection molding is used for thermoplastics, whereas compression molding is used for the thermoset plastics. See Chap. 4, "Materials and Their Uses," and Chap. 12, "Castings, Moldings, Extrusions, and Powder-Metal Technology," for more information on the various casting alloys and plastics used in molding processes.

Figure 8.53 shows a typical machined form used to make the tooling epoxy mold to mold other types of epoxy plastics. Forms or master patterns such as that shown in this figure are normally made of 2024 or 7075 aluminum alloys, although other materials may be used. The high-quality aluminum alloys were used on this master pattern owing to their excellent strength and easy machinability. This particular master pattern was machined on a CNC machining center and assembled by a master die maker.

Figure 8.54 shows another master pattern used for making tooling epoxy molds. In this example, the pattern was produced on a CNC turning center using a program written by the tool engineering department. It should be noted that no additional finishing was required on this master pattern. The extremely smooth and polished surfaces were produced with carbide cutting tools in a multiple-pass operation.

8.10 Force Gauge for Tooling Applications

It is often necessary to know the pressures or forces actually required to operate specific types of tooling devices. This information is of benefit to the tool design engineer and master die maker. Strain gauges and "load cells" normally are required to determine accurately the

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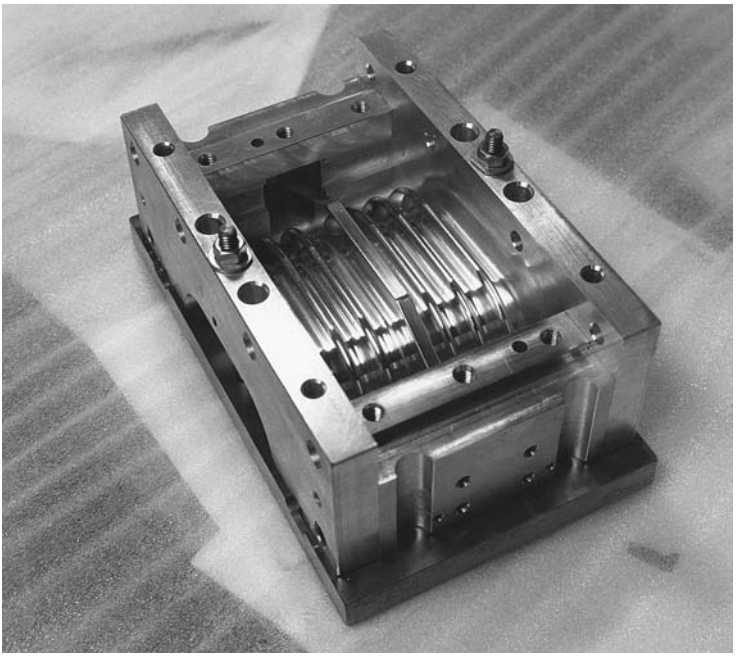

Figure 8.53 A mold form.

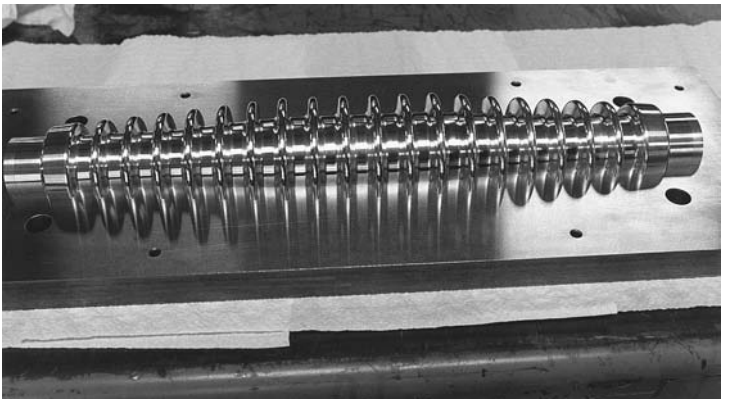

Figure 8.54 Master metal pattern for producing plastic molds.

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Figure 8.55 Two hydraulic force gauges.

forces applied to various components in operation. A simple, inexpensive type of hydraulic force gauge may be constructed by the die maker for this application. Figure 8.55 shows two hydraulic force gauges with different ranges, as indicated on the dials of the gauges.

8.11 Complex Molds for Plastic Parts

The molds for intricate plastic parts are difficult to design and produce, but the processes are greatly aided by modern machining centers and turning centers that are CNC controlled. A large amount of tooling expertise and experience is required to produce molds such as that shown in Fig. 8.56. The figure illustrates a compound mold for producing the parts shown in Fig. 8.57, which are electrical equipment bus-bar bushings made from cycloaliphatic epoxy resin. Figure 8.58 pictures another complex, compound mold, used for producing the parts shown in Figure 8.59. These parts are made of clear acrylic plastic and are shown assembled into an electrical power interruption unit known as an "arc-chute." The arc-

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Tooling, Die Making, Molds, Jigs, and Fixtures

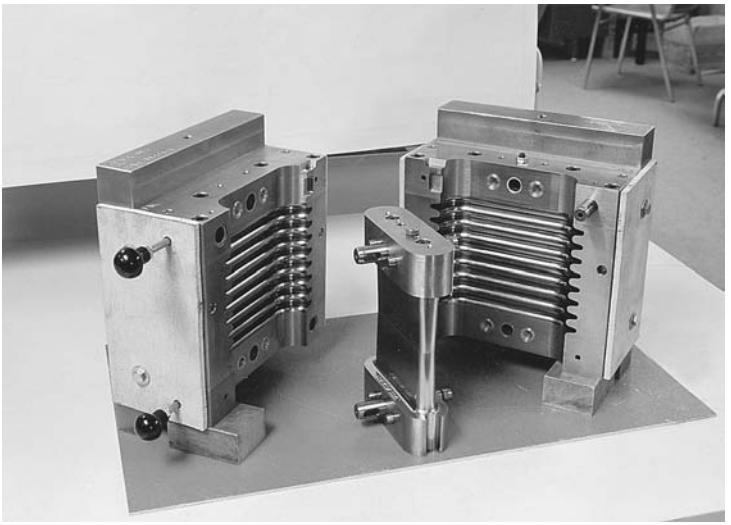

Figure 8.56 A complex, compound mold for the parts shown in Fig. 8.57.

chute assemblies are parts of a three-phase high-voltage interrupter switch used in the electrical power distribution industry. Refer to the tool-steel selection section of this chapter (Sec. 8.2) to determine the types of tool steels generally used to produce such molds.

8.12 The Five Major Rules of Die Making

Tooling practices and die making are exacting arts and sciences. The tool design engineer and tool and die maker require great skill, knowledge, and experience. Several designs may be possible for any particular tooling and die-making problem, but there is usually only one solution that is best for the given conditions and tooling objectives. With this in mind, the following five major tooling and die-making rules will help the new tool designer and die maker to achieve his or her goals:

1 Define the stamping or die-making problem correctly.

2. Select the design that is best for all conditions.

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Figure 8.57 Plastic parts (cycloaliphatic epoxy) made from the mold shown in Fig. 8.56.

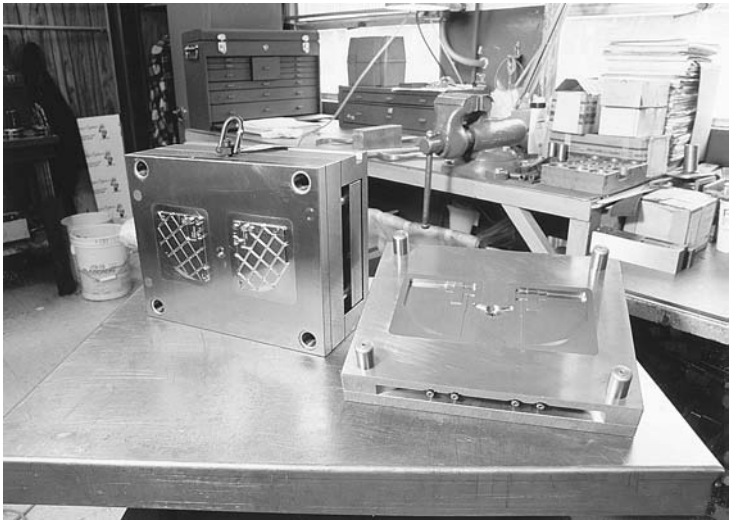

Figure 8.58 A complex, compound mold for the acrylic plastic parts shown in Fig. 8.59.

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Tooling, Die Making, Molds, Jigs, and Fixtures

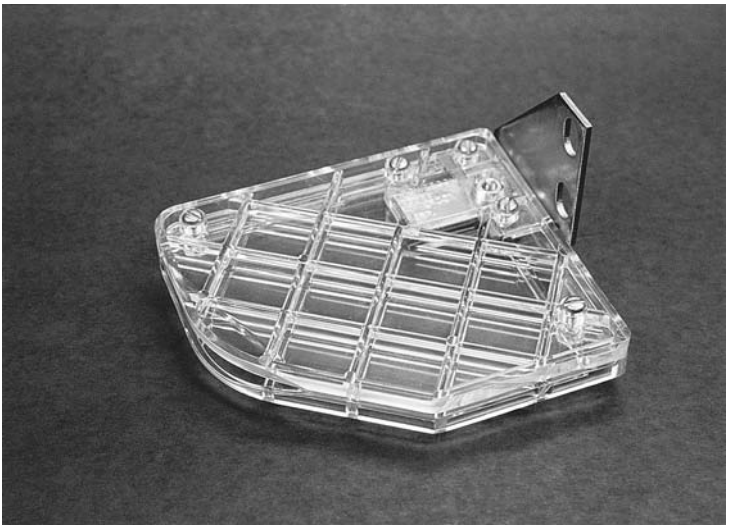

Figure 8.59 Acrylic plastic parts made from the mold shown in Figure 8.58.

3. Permit the fabrication of the die parts without difficulty.
4. The finished parts of the die must be assembled easily by the die maker.
5. The tool or die must function well and solve the stamping, tool, or die problem exactly as intended.

Clean and precise working drawings of the die and all its parts must be produced by the tool engineering department, and the die maker must transform these drawings into an accurate working die using the information provided by the tooling engineer and the die maker's own experience and skill.

The production of functional and accurate parts, through tooling, is the beginning of and the most important part of a sometimes long and complex process that determines the success of the finished product.

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Chapter

9

Sheet Metal Practices and Layout

The branch of metalworking known as sheet metal comprises a large and important element. Sheet metal parts are used in countless commercial and military products. Sheet metal parts are found on almost every product produced by the metalworking industries throughout the world.

Sheet metal gauges run from under 0.001 to 0.500 in. Hot-rolled steel products can run from ½ in thick to no. 18 gauge (0.0478 in) and still be considered as "sheet." Cold-rolled steel sheets generally are available from stock in sizes from no. 10 gauge (0.1345 in) down to no. 28 gauge (0.0148 in). Other sheet thicknesses are available as special-order "mill run" products when the order is large enough. Large manufacturers who use vast tonnages of steel products such as the automobile makers, switch-gear producers, and other sheet metal fabricators may order their steel to their own specifications (composition, gauges, and physical properties).

The steel sheets are supplied in flat form or rolled into coils. Flat-form sheets are made to specific standard sizes unless ordered to special nonstandard dimensions.

9.1 Carbon and Low-Alloy Steel Sheets

Carbon steel sheets and coils are produced in the following grades or classes:

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Hot rolled

- Low carbon (commercial quality)
- Pickled and oiled
- 0.40/0.50 carbon
- Abrasion resistant
- Hi-Form (A715), high strength/low alloy (grades 50 and 80)
- A607 specification, high strength/low alloy (INX 45, INX 50, ExTen 50)
- A606 specification, high strength/low alloy (Cor-Ten)

Note: The code numbers indicate the yield strength of the high strength/low-alloy steels; i.e., INX 45 = 45,000 psi yield; grade 80 = 80,000 psi yield.

Cold rolled

- Low carbon (commercial quality)
- Special killed (drawing quality)
- Auto prototype (special killed drawing quality)
- Vitreous enameling
- Plating quality
- Stretcher leveled

The applications for the previously listed sheet steels are as follows:

Hot-rolled applications

Low carbon (commercial quality). Conforms to American Society for Testing and Materials (ASTM) A569 and is used for tanks, barrels, farm implements, and other applications where surface quality is not critical or important.

Pickled and oiled. Conforms to ASTM A569 and is used for automotive parts, switch gear, appliances, toys, and other applications where a better surface quality is required and paint and enamel adhere well. Carbon content is 10 percent maximum, and this material may be formed easily and welded the same as low-carbon sheet (commercial quality).

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Sheet Metal Practices and Layout

0.40/0.50 carbon. Has 50 percent more yield strength and abrasion resistance than low-carbon sheets. May be heat-treated for more strength and hardness. Used for scrapers, blades, tools, and other applications requiring a strong, moderate-cost steel sheet.

Abrasion resistant. Medium carbon content and higher manganese greatly improve resistance to abrasion. Brinell hardness = 210 minimum. Uses include scrapers, liners, chutes, conveyors, and other applications requiring a strong, abrasion-resistant steel sheet. Formability is moderate.

A607 specification. Lowest-cost low-alloy steel sheet. Low carbon content ensures good formability. Excellent weldability. Typical uses include utility poles, transmission towers, automotive parts, truck trailers, and other applications requiring a low-cost, high strength alloy steel sheet.

A606 specification. Five times more resistant to atmospheric corrosion than low-carbon steel. Excellent weldability and formability.

A715 specification. Fine-grained columbium-bearing series of high-strength steel. Enhanced bending and forming properties. Tough and fatigue resistant, with excellent weldability using all welding processes. Yield-point levels range from 40,000 to 80,000 psi.

Cold-rolled applications

Low carbon (commercial quality). Produced with a high degree of gauge accuracy and uniform physical characteristics. Excellent surface for painting (enamel or lacquer). Good for stamping and moderate drawing applications. Improved welding and forming characteristics, with uses such as household appliances, truck bodies, signs, panels, and many other applications.

Special killed (drawing quality). Used for severe forming and drawing applications. Freedom from age hardening and fluting. Conforms to ASTM A365 specification.

Auto prototype (special killed drawing quality). Used for prototype work and other deep drawing applications. Closely controlled gauge thickness with better tolerances compared with commercial-quality grades.

Vitreous enameling. Cold rolled from commercially pure iron ingots for porcelain-enameled products. Textured surface and suitable for

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forming and moderate drawing applications and flatwork. Conforms to ASTM A424, grade A.

Plating quality. Two finishes are provided that are suitable for most plating applications: commercial bright and extralight matte.

Stretcher leveled. Uniform, high-quality matte sheets, further processed by stretching to provide superior flatness. Furnished resquared or not resquared. Resquared sheets have the stretching gripper marks removed. Used in the manufacture of table tops, cabinets, truck body panels, partitions, templates, and many other applications. Conforms to ASTM A336 specification.

Galvanized sheet and coil. The galvanic coating is zinc, and it is applied to standard steel sheets or coils in two basic methods: hot-dipped galvanized and electrogalvanized. The hot-dipped galvanized processes are known as *Ti-Co galvanized, galvanized bonderized, galvannealed, galvannealed A,* and *hot-dipped galvanized.* Galvanizing specifications are found in ASTM A526 and A527. Some of the hot-dipped sheets may have 1.25 oz zinc per square foot of surface area and others a lighter deposit.

Electrogalvanized sheets are cold-rolled steel sheets coated with zinc by electrolytic deposition and conform to ASTM A591. These sheets should be painted if they are to be exposed to outdoor conditions. These sheets can be formed, rolled, or stamped without flaking, peeling, or cracking of the zinc coating. These galvanized sheets have the same gauge thickness as cold-rolled sheets. Applications include cabinets, signs, light fixtures, and others where an excellent finish is required. Coating weight is typically 0.1 oz/ft^2, or each side is 0.00008 in thick. Trade names include Paint-Lok, Bethzin, Gripcoat, Lifecote 1, Weirzin Bonderized, and others.

Aluminized and long-terne sheets. Sheet steel is also aluminized and produced in long-terne sheets. Aluminized steel sheet is hot-dip coated on both sides with aluminum-silicon alloy by the continuous method. Strong and corrosion resistant, aluminized sheet is also inexpensive. The aluminum coating is typically 0.001 in thick on both sides, or 0.40 oz/ft^2. Aluminized sheet conforms to the ASTM A463 specification. Applications include dry kiln fan walls, dryers, incinerators, mufflers, and oven and space-heater components. Long-terne sheet is a soft steel coated with an 85 percent lead and 15 percent tin alloy for maximum ease in soldering. These long-terne sheets conform to ASTM A308 and are used for soldered

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Sheet Metal Practices and Layout

tanks, automotive accessories, hood and radiator work, and many other stamped and formed products.

As can be seen from the preceding descriptions of sheet steels that are available commercially, the selection of a particular steel for a particular sheet metal application is relatively easy. Not only are there a great number of different sheet metal stocks available, but special sheet steels may be ordered to your specifications when quantities are large enough to justify their production by American steel makers.

9.2 Nonferrous Sheet Metal

The nonferrous sheet metals include aluminum and aluminum alloys, copper and copper alloys, magnesium alloys, titanium alloys, and other special alloys. See Chap. 4, "Materials and Their Uses," for data and specifications on the nonferrous as well as the ferrous materials that are specified by the American Society for Testing and Materials (ASTM) and the Society of Automotive Engineers (SAE). Supplier catalogs are also available from companies such as Ryerson, Vincent, Atlantic, Alcoa, Reynolds, Anaconda, Chase, and others, and they may be selected from an industrial supplier master index such as the *Thomas Register of American Manufacturers.*

9.3 Machinery for Sheet Metal Fabrication

Some of the typical machinery found in a large manufacturing plant for processing and producing sheet metal parts includes

- Shears, hydraulic and squaring
- Press brakes
- Leaf brakes
- Roll-forming machines
- Automatic [computer numerical controlled (CNC)] multistation punch presses
- Single-die punch presses, strippit and unipunch setups
- Slitting machines
- Stretcher-bending machines
- Hydropresses (Marforming presses, Martin-Marietta Corp.)

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- Pin routers
- Yoder hammers
- Spin forming machines
- Tumbling and deburring machines
- Sand-blasting equipment
- Explosive forming facilities
- Ironworkers (for structural shapes)

The designer and tool engineer should be familiar with all machinery used to manufacture parts in a factory. These specialists must know the limitations of the machinery that will produce the parts as designed and tooled. Coordination of design with the tooling and manufacturing departments within a company is essential to the quality and economics of the products that are manufactured. Our modern machinery has been designed and is being improved constantly to allow us to manufacture quality products at affordable prices to consumers. Medium- to large-sized companies can no longer afford to manufacture products whose quality standards do not meet the demands and requirements of the end user.

9.3.1 Modern sheet metal manufacturing machinery

The processing of sheet metal begins with the hydraulic shear, where the material is squared and cut to size for the next operation. Figure 9.1 shows a typical hydraulic shear with the capacity to do a 120-in cut in up to no. 7 gauge steel sheet. These types of machines are the "workhorses" of the typical sheet metal department because all operations on sheet metal parts start at the shear.

Figure 9.2 shows a Wiedemann Optishear, which shears and squares sheet metal to a high degree of accuracy. Blanks used in blanking, punching, and forming dies are produced on this machine, as are other flat and accurate pieces that proceed to the next stage of manufacture.

The flat, sheared sheet metal parts then may be routed to punch presses, where holes of various sizes and patterns are produced. Figure 9.3 shows a medium-sized CNC multistation turret punch press, which is both highly accurate and very fast. (See Chap. 1, "Modern Metalworking Machinery and Measuring Devices," for other types of machinery used by the metalworking industry.)

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Figure 9.1 The hydraulic shear used to cut sheet metal.

Figure 9.2 A highly accurate squaring shear that is computer numerically controlled (CNC).

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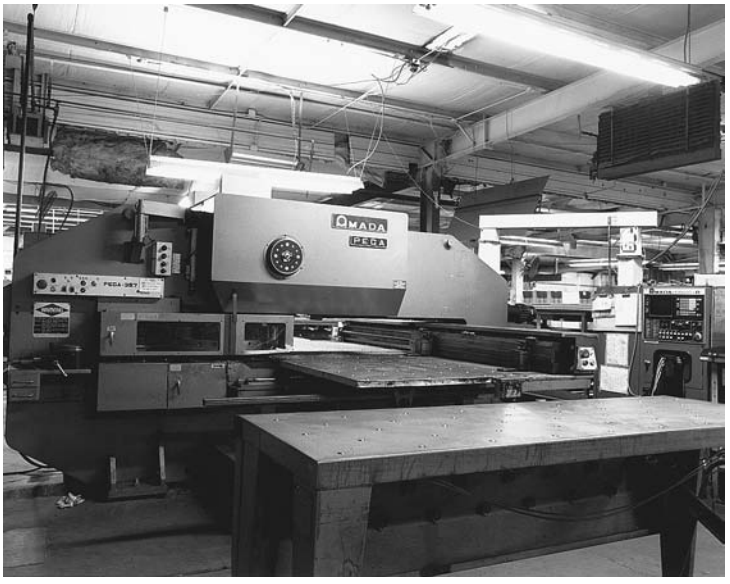

Figure 9.3 The Amada Pega high-speed CNC multistation punch press.

After a sheet metal part is sheared and punched, it may require a press-brake operation to form flanges or produce hemmed edges. Figure 9.4 shows a small press brake that has a digital readout for the "back-gauge" dimension. A small press brake such as this may be used for bending small sheet metal parts, flat bar stock, and copper and aluminum bus bars.

To quickly check a sheet metal gauge, either ferrous or nonferrous, a tool similar to that shown in Fig. 9.5 is used frequently in the sheet metal department. The tool gauge shown in the figure is for nonferrous metals such as stainless steel sheets and nonferrous wires.

9.4 Gauging Systems

To specify the thickness of different metal products such as steel sheets, wire, strip and tubing, music wire, and others, a host of gauging systems were developed over the course of many years. Shown in Fig. 9.6 are the common gauging systems used for commercial steel sheets, strip and tubing, and brass and steel wire. The steel sheets column in the figure lists the gauges and equivalent thicknesses

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Figure 9.4 A small press brake with digital back gauge.

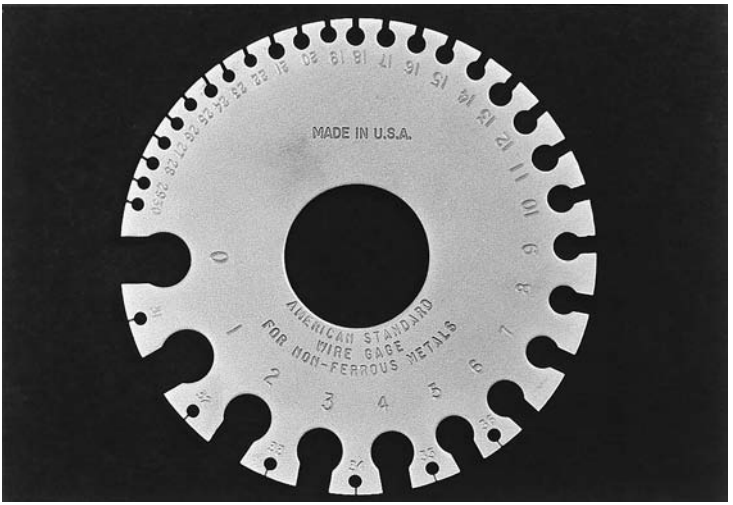

Figure 9.5 American standard wire-gauge-measuring tool.

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Gauge No.	Brass (Brown & Sharpe)	Steel Sheets *	Strip & Tubing	Steel Wire Ga. ♦
6-0	0.5800	--------	--------	0.4615
5-0	0.5165	--------	0.500	0.4305
4-0	0.4600	--------	0.454	0.3938
3-0	0.4096	--------	0.425	0.3625
2-0	0.3648	--------	0.380	0.3310
0	0.3249	--------	0.340	0.3065
1	0.2893	--------	0.300	0.2830
2	0.2576	--------	0.284	0.2625
3	0.2294	0.2391	0.259	0.2437
4	0.2043	0.2242	0.238	0.2253
5	0.1819	0.2092	0.220	0.2070
6	0.1620	0.1943	0.203	0.1920
7	0.1443	0.1793	0.180	0.1770
8	0.1285	0.1644	0.165	0.1620
9	0.1144	0.1495	0.148	0.1483
10	0.1019	0.1345	0.134	0.1350
11	0.0907	0.1196	0.120	0.1205
12	0.0808	0.1046	0.109	0.1055
13	0.0720	0.0897	0.095	0.0915
14	0.0641	0.0747	0.083	0.0800
15	0.0571	0.0673	0.072	0.0720
16	0.0508	0.0598	0.065	0.0625
17	0.0453	0.0538	0.058	0.0540
18	0.0403	0.0478	0.049	0.0475
19	0.0359	0.0418	0.042	0.0410
20	0.0320	0.0359	0.035	0.0348
21	0.0285	0.0329	0.032	0.0317
22	0.0253	0.0299	0.028	0.0286
23	0.0226	0.0269	0.025	0.0258
24	0.0201	0.0239	0.022	0.0230
25	0.0179	0.0209	0.020	0.0204
26	0.0159	0.0179	0.018	0.0181
27	0.0142	0.0164	0.016	0.0173
28	0.0126	0.0149	0.014	0.0162
29	0.0113	0.0135	0.013	0.0150
30	0.0100	0.0120	0.012	0.0140
31	0.0089	0.0105	0.010	0.0132
32	0.0080	0.0097	0.009	0.0128
33	0.0071	0.0090	0.008	0.0118
34	0.0063	0.0082	0.007	0.0104
35	0.0056	0.0075	0.005	0.0095
36	0.0050	0.0067	0.004	0.0090
37	0.0045	0.0064	--------	0.0085
38	0.0040	0.0060	--------	0.0080

*= Common Commercial Standard; ♦ = Reference only

Figure 9.6 Gauging decimal systems table.

used by American steel sheet manufacturers and steel makers. This gauging system can be recognized immediately by its no. 11 gauge equivalent of 0.1196 in, which is standard today for this very common and high-use gauge of sheet steel.

Figure 9.7 is a table of gauging systems that were used widely in the past, although some are still in use today, including the American

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or Brown and Sharpe system. The Brown and Sharpe system is also shown in Fig. 9.6, but there it is indicated in only four-place decimal equivalents.

9.4.1 Aluminum sheet metal standard thicknesses

Aluminum is used widely in the aerospace industry, and over the years, the gauge thicknesses of aluminum sheets have developed on their own. Aluminum sheet is now generally available in the thicknesses shown in Fig. 9.8. The fact that the final weight of an aerospace vehicle is very critical to its performance has played an important role in the development of the standard aluminum sheet gauges, wherein the strength-to-weight ratio is critical and a few thousandths of an inch extra on an aluminum sheet can mean more final weight of an aerospace vehicle. The gauges or thicknesses of other metals and alloys, together with their stock tolerances, are given in Chap. 4, "Materials and Their Uses."

9.5 Methods of Sheet Metal Fabrication

Many methods have been developed for working or fabricating sheet metal parts, including those employed to cut, punch, and form sheet metal parts.

9.5.1 Sheet metal cutting methods

Shearing. The sheet metal stock sheet is cut on a hydraulic-powered shear to its appropriate blank size or minimum size for punching or profiling the part. See Figs. 9.1 and 9.2 for hydraulic shears.

Slitting. The sheet metal stock sheet is run through a slitting machine, where accurate widths are slit with slitting knives to various lengths. The slit edges are sharp and accurate, with excellent straightness along both edges. Slit sheet metal is usually fed directly into the feed gates of punching or bending dies or roll-forming equipment. The roll-forming machine produces a specific type of cross-sectional shape to the finished part. Samples of roll-formed parts can be seen in Fig. 9.15.

Welding-process cutting and water-jet cutting. The sheet metal stock sheet may be oxyacetylene torch cut with an automatic torch cutting machine, or it may be plasma cut, arc cut, or waterjet cut.

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Number of wire gauge	American or Brown & Sharpe	Birmingham or Stubs' Iron wire	Washburn & Moen, Worcester, Mass.	W. & M. steel music wire	American S. & W. Co's. music wire gauge	Stubs' steel wire	U.S. Standard gauge for sheet and plate iron and steel	Number of wire gauge
00000000				0.0083				00000000
0000000				0.0087				0000000
000000				0.0095	0.004		0.46875	000000
00000				0.010	0.005		0.4375	00000
0000	0.460	0.454	0.3938	0.011	0.006		0.40625	0000
000	0.40964	0.425	0.3625	0.012	0.007		0.375	000
00	0.3648	0.380	0.3310	0.0133	0.008		0.34375	00
0	0.32486	0.340	0.3065	0.0144	0.009		0.3125	0
1	0.2893	0.300	0.2830	0.0156	0.010	0.227	0.28125	1
2	0.025763	0.284	0.2625	0.0166	0.011	0.219	0.265625	2
3	0.22942	0.259	0.2437	0.0178	0.012	0.212	0.250	3
4	0.20431	0.238	0.2253	0.0188	0.013	0.207	0.234375	4
5	0.18194	0.220	0.2070	0.0202	0.014	0.204	0.21875	5
6	0.16202	0.203	0.1920	0.0215	0.016	0.201	0.203125	6
7	0.14428	0.180	0.1770	0.023	0.018	0.199	0.1875	7
8	0.12849	0.165	0.1620	0.0243	0.020	0.197	0.171875	8
9	0.11443	0.148	0.1483	0.0256	0.022	0.194	0.15625	9
10	0.10189	0.134	0.1350	0.027	0.024	0.191	0.140625	10
11	0.090742	0.120	0.1205	0.0284	0.026	0.188	0.125	11
12	0.080808	0.109	0.1055	0.0296	0.029	0.185	0.109375	12
13	0.071961	0.095	0.0915	0.0314	0.031	0.182	0.09375	13
14	0.064084	0.083	0.0800	0.0326	0.033	0.180	0.078125	14

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15	0.057068	0.072	0.0720	0.0345	0.035	0.178	0.0703125	15
16	0.05082	0.065	0.0625	0.036	0.037	0.175	0.0625	16
17	0.045257	0.058	0.0540	0.0377	0.039	0.172	0.05625	17
18	0.040303	0.049	0.0475	0.0395	0.041	0.168	0.050	18
19	0.03589	0.042	0.0410	0.0414	0.043	0.164	0.04375	19
20	0.031961	0.035	0.0348	0.0434	0.045	0.161	0.0375	20
21	0.028462	0.032	0.03175	0.046	0.047	0.157	0.034375	21
22	0.025347	0.028	0.0286	0.0483	0.049	0.155	0.03125	22
23	0.022571	0.025	0.0258	0.051	0.051	0.153	0.028125	23
24	0.0201	0.022	0.0230	0.055	0.055	0.151	0.025	24
25	0.0179	0.020	0.0204	0.0586	0.059	0.148	0.021875	25
26	0.01594	0.018	0.0181	0.0626	0.063	0.146	0.01875	26
27	0.014195	0.016	0.0173	0.0658	0.067	0.143	0.0171875	27
28	0.012641	0.014	0.0162	0.072	0.071	0.139	0.015625	28
29	0.011257	0.013	0.0150	0.076	0.075	0.134	0.0140625	29
30	0.010025	0.012	0.0140	0.080	0.080	0.127	0.0125	30
31	0.008928	0.010	0.0132		0.085	0.120	0.0109375	31
32	0.00795	0.009	0.0128		0.090	0.115	0.01015625	32
33	0.00708	0.008	0.0118		0.095	0.112	0.009375	33
34	0.006304	0.007	0.0104			0.110	0.00859375	34
35	0.005614	0.005	0.0095			0.108	0.0078125	35
36	0.005	0.004	0.0090			0.106	0.00703125	36
37	0.004453					0.103	0.006640625	37
38	0.003965					0.101	0.00625	38
39	0.003531					0.099		39
40	0.003144					0.097		40

Figure 9.7 Other gauging systems.

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Standard Thickness, in.	Weight, lbs/sq. ft.
0.010	0.141
0.016	0.226
0.020	0.282
0.025	0.353
0.032	0.452
0.040	0.564
0.050	0.706
0.063	0.889
0.071	1.002
0.080	1.129
0.090	1.270
0.100	1.411
0.125	1.764
0.160	2.258
0.190	2.681
0.250	3.528

Weight based on an average aluminum weight of 0.098 lb/in^3.

Figure 9.8 Standard aluminum sheet metal thicknesses and weights.

All these methods are used today to cut both metallic and nonmetallic flat sheet parts.

Laser-beam cutting. The technology of laser-beam cutting of sheet metal flat stock has progressed dramatically in the past 5 years. The older laser-cutting machines produced a ragged edge, which made parts processing difficult. The newer laser-cutting machines can cut a variety of sheet metal stocks, including steel, aluminum, stainless steel, and nonmetallic parts, while achieving excellent accuracy and edge qualities. Laser cutting allows sheet metal parts to be cut to a level of accuracy that would not be possible using conventional punch presses or other equipment.

Figure 9.9 shows a laser-cutting machine. Note the CNC control panel on the right side of the illustration of the machine. Figure 9.10 shows a close-up view of the laser-cutting machine actually cutting a steel sheet metal part. A drawing of this part is shown in Fig. 9.11. The cleanly cut edges of this part are shown in Fig. 9.12. Accuracy of the laser-cut parts is excellent, as are the edge qualities.

Laser-cut parts may be processed on the laser machine by using programs that will allow coordinates of AutoCad drawings of flat sheet metal or bar stock parts to be placed into the CNC controller of the laser machine, wherein the machine will exactly duplicate

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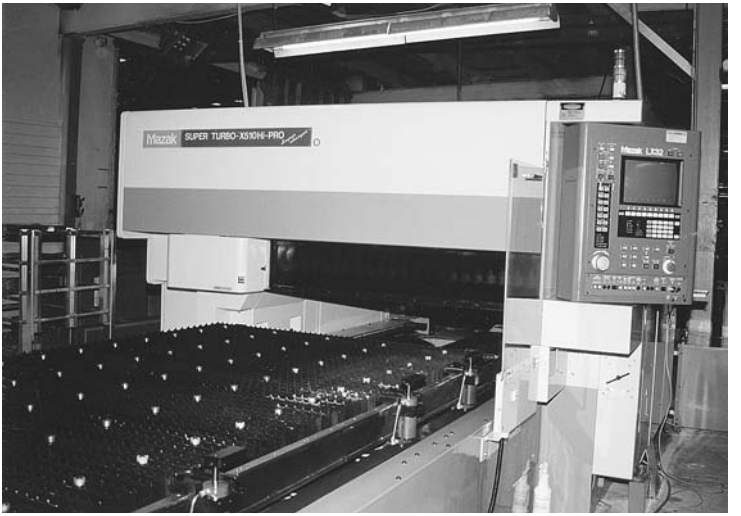

Figure 9.9 A modern laser-cutting machine with CNC controller.

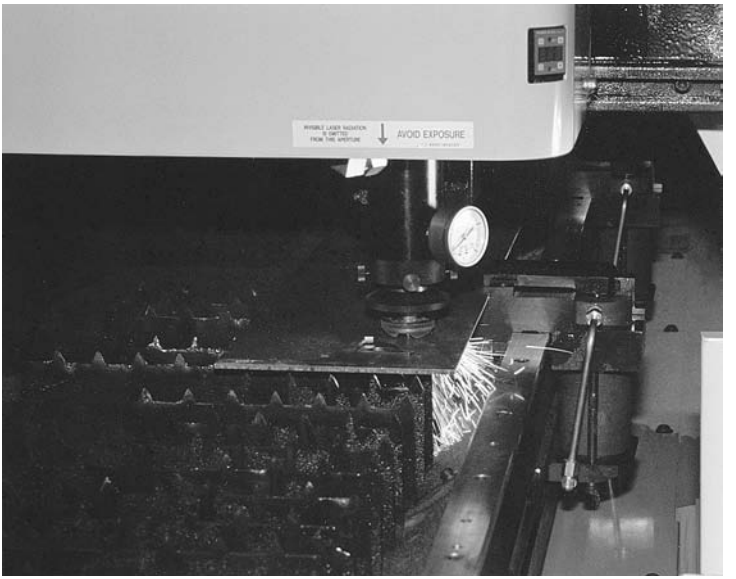

Figure 9.10 Close-up view of laser-cutting machine cutting the part shown in Figs. 9.11 and 9.12.

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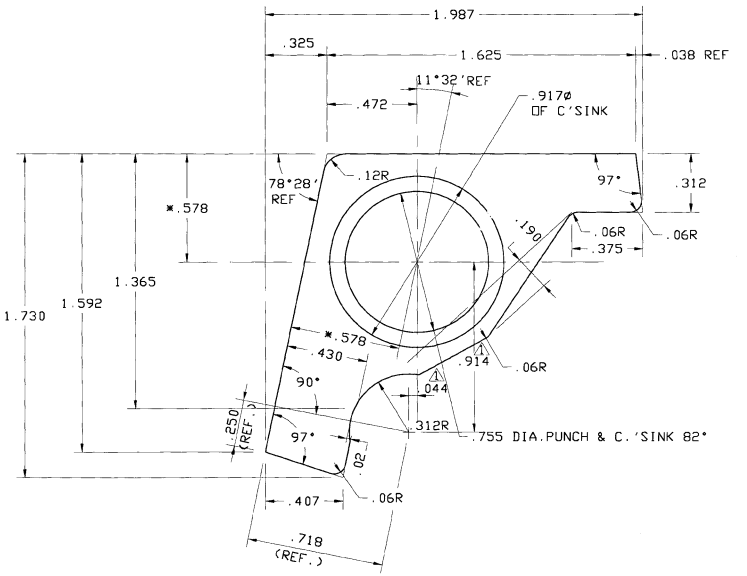

Figure 9.11 A scaled AutoCad drawing for a laser-cutting operation.

Figure 9.12 A laser-cut part based on the drawing in Fig. 9.11, showing the smooth, accurate cut.

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the parts per the AutoCad drawing. The AutoCad drawings must be drawn to scale to allow this procedure to take place. Using this process, intricate sheet metal parts can be produced economically in quantities too small to justify use of a hard die. The laser-cutting machine shown in Fig. 9.9 will cut different steel sheet metal, plate, or bar stock up to 0.375 in thick. Larger laser-cutting machines can cut even thicker stock material.

Laser-cutting machines allow the design engineer and tool engineer to design and produce parts that would not have been economically possible using older methods of cutting and punching. Figure 9.13 is a drawing of a very complex flat pattern of a sheet metal part that normally would have to be produced from a hard die. The laser-cutting machine can produce this part in no.7 gauge sheet steel in about 1 minute.

Caution: You should wear protective plastic glasses when watching a laser-cutting machine in operation. Glass lenses will not block the radiation leaking from the machine. Normal plastic lenses are suitable. Laser-cutting machines display a caution warning sign in the area of the cutting head.

Other methods of cutting sheet metal. Additional processes include hard-die punching, strippit and turret-press punching, and pin

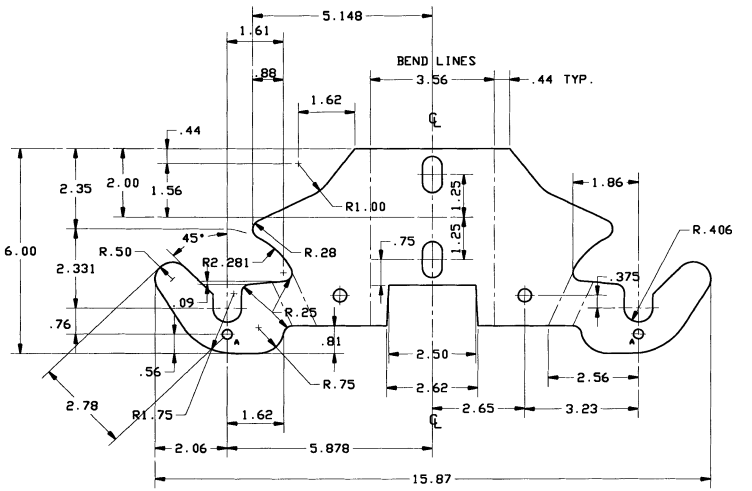

Figure 9.13 An AutoCad scale drawing for a complex laser-cut sheet metal part.

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routing. Pin routing is used to cut a stack of thin aluminum alloy sheets from a pattern made from a loft. The pin-routing procedure is actually a tracer-milling operation. This practice is used in the aircraft and aerospace industries.

9.5.2 Sheet metal punching methods

Turret punch. The sheet metal stock sheet or blank is punched with various holes of different shapes by the punching dies contained on the punch press. Punch presses usually have a revolving turret that contains punches of different sizes and shapes, and these are interchangeable. The modern multistation punch presses are often CNC controlled and high speed.

Die punch. The sheet metal blank is placed in a punching die, where a pattern of holes is punched simultaneously with one stroke of the punching press. The high-tonnage brake press is often used to provide the power stroke required on the punching die block.

Strippit punch. The sheet metal blank is punched, one hole at a time, on a strippit punch press. The punching dies may be changed quickly for punching different sizes or shapes of holes, such as round, square, rectangular, oval, or obround, or other special shapes for which the dies are designed.

9.5.3 Sheet metal forming methods

Press brake. This type of machine tool is found in every sheet metal department and is used to bend flanges, hems, and other special shapes. Figure 9.14 shows the various bending abilities of the press brake when equipped with the proper tooling.

Die bending, forming, and molding. Hard dies are produced for making bends and molds and for forming and drawing sheet metal parts. The forming or drawing dies may be all metal or a combination of metal and neoprene pads, which force the metal against the die block or male form. This process is used widely in the aerospace industry, where aluminum sheet metal parts are formed on hydropresses. (Marforming is a hydropressing process originated at the Martin Company, Middle River, MD.) Large lead-alloy form blocks are also used in the aircraft industry to form large, compound curved surfaces in sheet metal, generally aluminum alloys.

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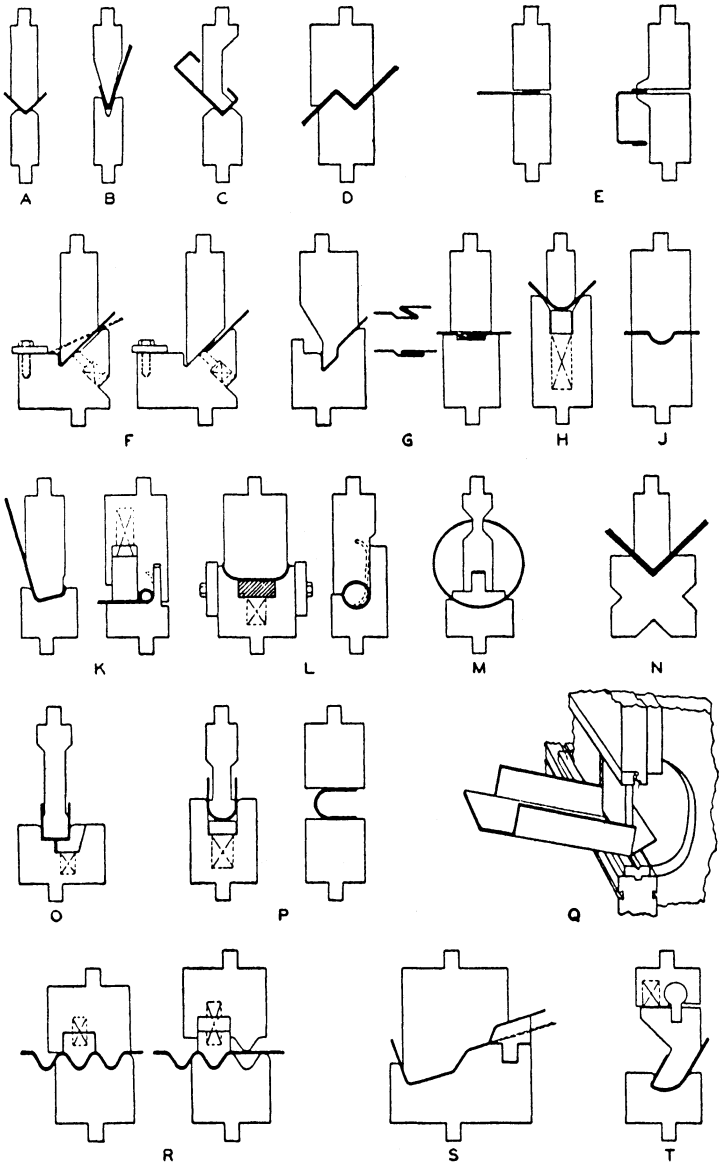

Figure 9.14 Press brake bending dies showing bending capabilities of the press brake.

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Yoder hammering. This is a specialized metal forming operation where a rapidly moving set of vertical forming hammers of various shapes is used to form special surfaces on sheet metal sections in a hammering process. This is a manual operation that requires operator skill and practice and is relatively rare today.

Spin forming. In this sheet metal forming process, a sheet metal disk is rotated in a special type of lathe tool while a special forming tool is pressed against the rotating disk of metal in a rotary swaging operation, thus forming or spin-drawing the part to the required shape. The process is limited to metal sections that are of a symmetric rotated section of revolution, such as bell shapes, cones, parabolic sections, cylinders, etc.

Explosive forming. In this process of metal forming, a shaped charge of explosive is suspended above a sheet metal flat pattern, both of which are submerged under water. When the explosive charge is detonated, the shock waves from the explosion exert a hydrostatic pressure against the sheet metal, forcing it against a forming die block almost instantaneously. The sheet metal part conforms to the shape of the die block. Very complex sheet metal parts may be formed with this process. Some companies in the United States are devoted entirely to this specialized form of sheet metal fabrication. This process dates back to the 1950s, when it was used by the Martin Company, Middle River, MD, in its aircraft manufacturing facilities.

Stretcher bending. This process for sheet metal forming uses a machine known as a *stretcher bender,* wherein a sheet metal formed section such as an angle, channel, or Z section is pulled against a radiused die block to accurately form structural frame sections to a specified radius of curvature. The frame structures of rockets and aerospace vehicles, which have a single radius of curvature, are formed on the stretcher-bending machine. This is the only cost-effective method known for producing such sheet metal frame parts quickly and accurately on a relatively simple machine. In this operation, the straight frame section that was press-brake bent is held in a set of grippers at each end of the part. The part is stretched and pulled against the radiused die block simultaneously by the gripper arms, thus forming the part to the specified radius. Allowance is made for "springback" of the formed part by overbending and then allowing the metal to spring back or return to the correct form.

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Roll forming. In the roll-forming process, a flat strip of sheet metal is fed into the roll-forming machine, which has a series of rolling dies whose shape gradually changes as the metal is being fed past each stage of rolls until the final roll-formed section is completed. The number of different cross sections of roll-formed sheet metal parts is limitless. The roll-formed part is usually made to a specific length or stock length or may be produced to any special length required. Figure 9.15 is a sample page of roll-formed sections taken from the Dahlstrom catalog of molded and rolled sections (Dahlstrom Manufacturing Corporation, Jamestown, NY).

A sample of sheet metal parts that have been press-brake bent and die formed may be seen in photographs shown in Chap. 8, "Tooling, Die Making, Molds, Jigs, and Fixtures."

9.6 Sheet Metal Flat Patterns

The correct determination of the flat-pattern dimensions of a sheet metal part that is formed or bent is of prime importance to sheet metal workers, designers, and design drafters. There are three methods for performing the calculations to determine flat patterns that are considered normal practice. The method chosen also can determine the accuracy of the results. The three common methods employed for doing the work include

- By bend deduction (BD) or setback
- By bend allowance (BA)
- By inside dimensions or inside mold line (IML) for sharply bent parts only

Other methods are also used for calculating the flat-pattern length of sheet metal parts. Some take into consideration the ductility of the material, and others are based on extensive experimental data for determining the bend allowances. The methods included in this section are accurate when the bend radius has been selected properly for each particular gauge and condition of the material. When the proper bend radius is selected, there is no stretching of the *neutral axis* within the part (the neutral axis is generally accepted as being located 0.445 × material thickness inside the inside mold line (IML) (see Fig. 9.17).

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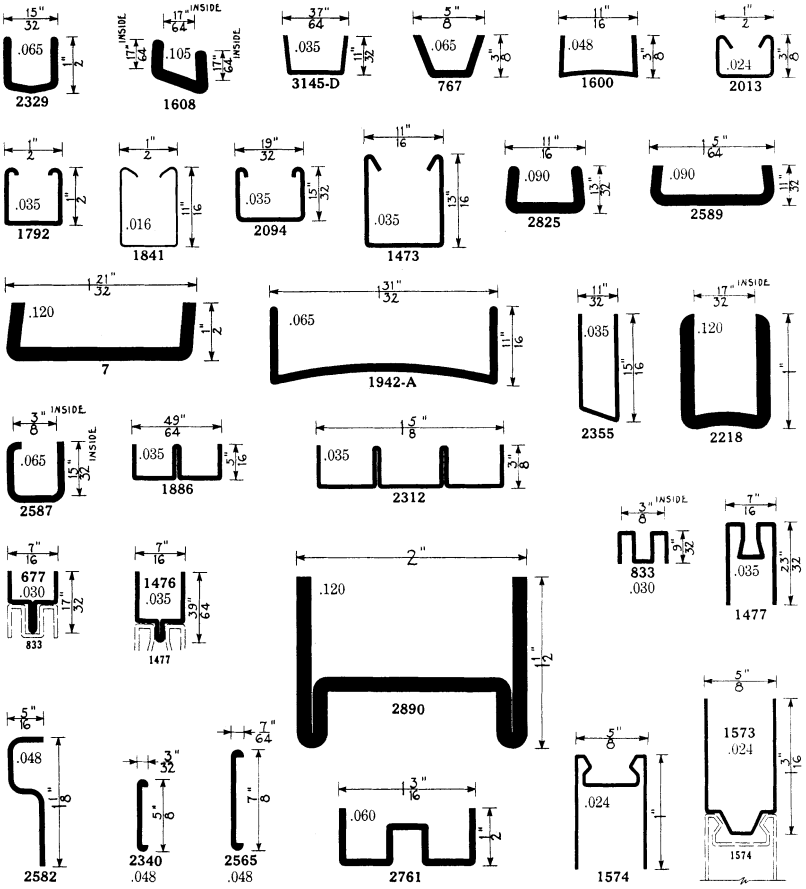

Figure 9.15 Samples of roll-formed sections of sheet metal.

Methods of determining flat patterns. Refer to Fig. 9.16.

Method 1: By bend deduction (BD) or setback

$$L = a + b - \text{setback}$$

Method 2: By bend allowance (BA)

$$L = a' + b' + c$$

where c is the bend allowance or length along the neutral axis.

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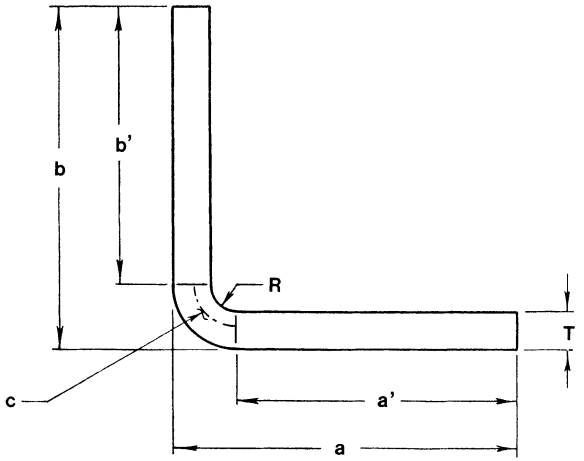

Figure 9.16 Sample of a bent sheet metal angle.

Method 3: By inside dimensions or inside mold line (IML)

$$L = (a - T) + (b - T)$$

Calculation of bend allowance and bend deduction (setback) is keyed to Fig. 9.17 and is as follows:

$$\text{Bend allowance (BA)} = A(0.01745R + 0.00778T)$$

$$\text{Bend deduction (BD)} = (2 \tan \tfrac{1}{2}A)(R + T) - (\text{BA})$$

$$X = (\tan \tfrac{1}{2}A)(R + T)$$

$$\text{Z} = \text{T}(\tan \tfrac{1}{2}A)$$

$$Y = X - Z \quad \text{or} \quad R(\tan \tfrac{1}{2}A)$$

On "open" angles that are bent less than 90° (Fig. 9.18),

$$X = (\tan \tfrac{1}{2}A)(R + T)$$

The method used to calculate the sheet metal flat pattern may be determined by designer option, company standards, order of accuracy, and method of manufacture. For soft steel (1010, etc.), the inside dimension method (method 3) is used whenever the material may be bent with a sharp or minimal inside bend radius (0.062 in or less). The inside bend method is accurate enough for all gauges

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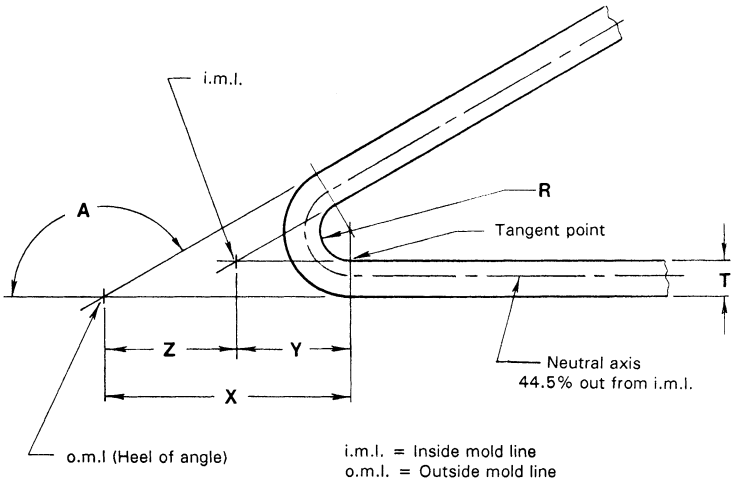

Figure 9.17 Geometry of a bend angle.

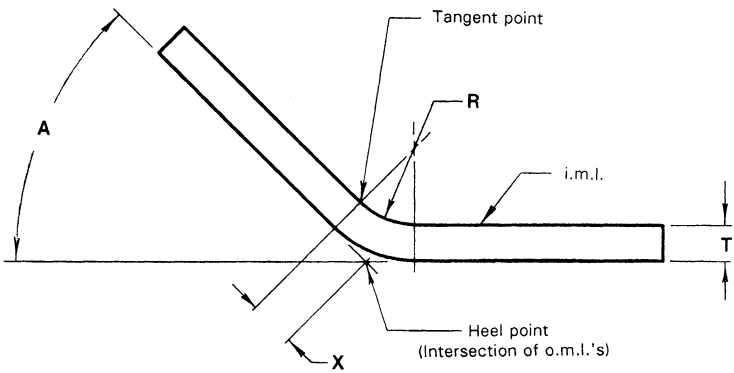

Figure 9.18 An open angle.

up to and including 0.375-in-thick stock where the tolerance of bent parts is ±0.032 in. On stock thicknesses from no. 7 gauge to 0.375 in, 0.062 in is added to the sum of the inside bend dimensions and divided across the bend, 0.032 in going into each leg or flange inside dimension. The 0.062-in allowance is added for each 90° bend in the part. This method is popular in such industries as the electrical switch-gear industry, the appliance industry, and others where great accuracy is not required.

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For very accurate flat-pattern dimensions intended for aerospace vehicles, automotive work, appliances, and other consumer products, the bend deduction or setback method is used in *lofting* procedures and standard sheet metal tooling drawings. The tooling department is usually responsible for generating the flat-pattern drawings of parts produced with stamping dies, punching dies, and drawing dies. The engineering department is usually responsible for generating the lofting drawings for flat patterns of regular and irregular shapes. In lofting, the part is drawn very accurately in flat pattern on flat metal sheets with specially prepared surfaces or directly onto heavy Mylar drafting film. The loft, or drawing, is then photographed, and the pattern is transferred to another metal sheet in full scale.

The part is then accurately cut out and becomes a master pattern. A stack of sheets then can be pin-routed or tracer-milled using the master template as a guide or jig. The cutout parts then are sent to the forming dies or the brakes for the final bending or forming operations. With modern CNC equipment, the part outline may be programmed and then cut automatically on the appropriate machine prior to the bending or forming operations.

When the sheet metal part is to be press-brake bent only on radiused bending dies, the bend allowance method can be used to calculate the flat pattern whenever accuracy and a specific inside bend radius are required. Bend deduction or setback also may be used in this case.

9.6.1 Setback or J chart for determining bend deductions

Figure 9.19 shows a form of bend deduction (BD) or setback chart known as a *J chart*. You may use this chart to determine bend deduction or setback when the angle of bend, material thickness, and inside bend radius are known. The chart in the figure shows a sample line running from the top to the bottom and drawn through the 3/16-in radius and the material thickness of 0.075 in. For a 90° bend, read across from the right to where the line intersects the closest curved line in the body of the chart. In this case, it can be seen that the line intersects the curve whose value is 0.18. This value is then the required setback or bend deduction for a bend of 90° in a part whose thickness is 0.075 in with an inside bend radius of 3/16-in. If we compute this setback or bend deduction value using the appropriate equations shown previously, we can check the value given by the J chart.

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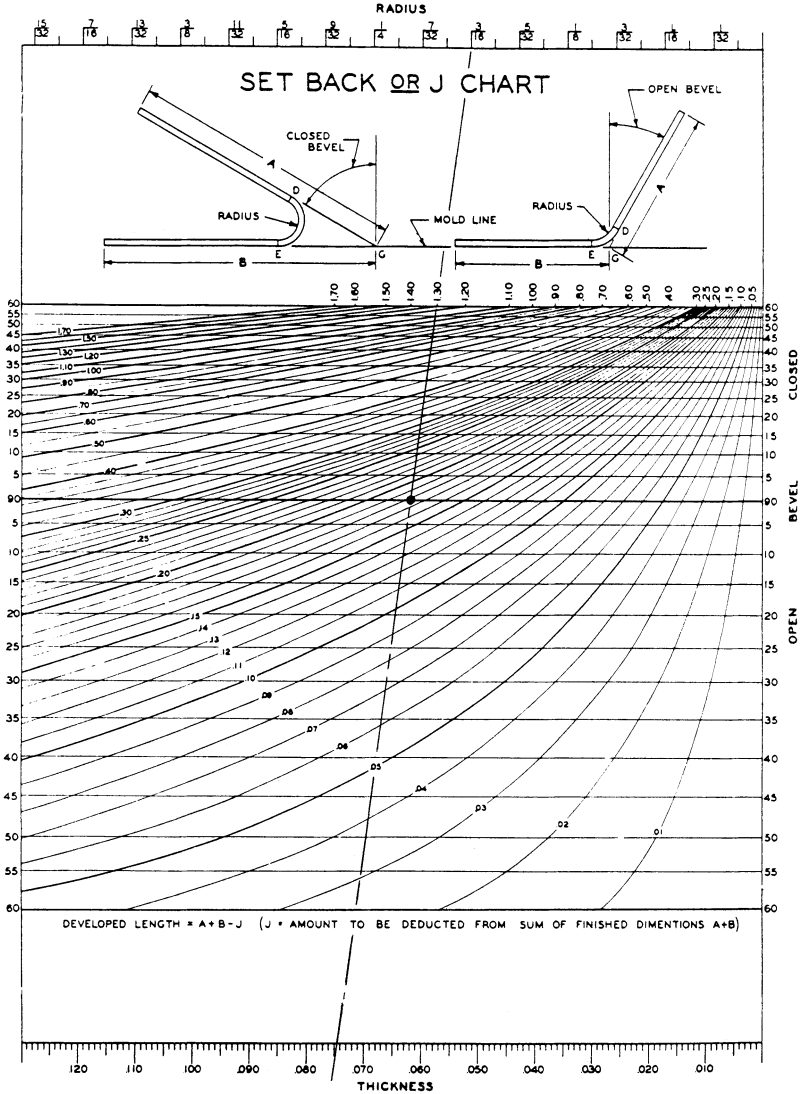

Figure 9.19 Setback or J chart.

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Checking: Bend deduction (BD) or setback is given as

$$\text{Bend deduction or setback} = (2 \tan \tfrac{1}{2}A)(R + T) - (\text{BA})$$

We first must find the bend allowance (BA) from

$$\begin{aligned}\text{Bend allowance} &= A(0.01745R + 0.00778T)\\ &= 90(0.01745 \times 0.1875 + 0.00778 \times 0.075)\\ &= 90(0.003855)\\ &= 0.34695\end{aligned}$$

Now, substituting the bend allowance of 0.34695 in into the bend deduction equation yields

$$\begin{aligned}\text{Bend deduction or setback} &= [2 \tan \tfrac{1}{2}(90)](0.1875 + 0.075) - 0.34695\\ &= 0.178 \text{ or } 0.18, \text{ as shown in the chart (Fig. 9.19)}\end{aligned}$$

The J chart in Figure 9.19 is thus an important tool for determining the bend deduction or setback of sheet metal flat patterns without recourse to tedious calculations. The accuracy of this chart has been shown to be of a high order. This chart as well as the equations were developed after extensive experimentation and practical working experience in the aerospace industry.

9.6.2 Bend radii for aluminum-alloy and steel sheet (average)

Figures 9.20 and 9.21 show average bend radii for various aluminum alloys and steel sheets.

9.7 Sheet Metal Developments and Transitions

The layout of sheet metal as required in "development and transition" parts is an important phase of sheet metal design and practice. The methods included here will prove useful in many design and working applications. These methods have application in duct work, aerospace vehicles, automotive equipment, and other areas of product design and development requiring the use of transitions and developments.

When sheet metal is to be formed into a curved section, it may be laid out, or *developed,* with reasonable accuracy by triangulation if it

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Material Gauge	Steel Designation	
	AISI 1020	302-303-304S/S
0.010	0.031	0.031
0.020	0.031	0.031
0.030	0.031	0.031
0.040	0.031	0.031
0.050	0.031	0.031
0.060	0.031	0.062
0.070	0.031	0.062
0.080	0.031	0.062
0.090	0.062	0.062
0.120	0.062	0.125
0.190	0.125	0.250
0.250	0.125	0.250

Figure 9.20 Bend radius table for sheet metal.

Material Gauge	Aluminum Alloy Designation		
	6061-T6 5052-H36 1100-H18	5052-H22 3003-H14	2024-T3
0.010	0.062	0.031	0.062
0.020	0.062	0.031	0.062
0.030	0.062	0.031	0.125
0.040	0.125	0.031	0.250
0.050	0.125	0.031	0.250
0.070	0.250	0.062	0.250
0.080	0.250	0.062	0.375
0.090	0.375	0.125	0.375
0.120	0.375	0.125	0.500
0.190	0.750	0.250	0.750
0.250	1.000	0.500	1.000

Figure 9.21 Bend radius table for aluminum sheet.

forms a simple curved surface without compound curves or curves in multiple directions. Sheet metal curved sections are found on many products, and if a straight edge can be placed flat against elements of the curved section, accurate layout or development is possible using the methods shown in this section.

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On double-curved surfaces such as are found on automobile and truck bodies and aircraft, forming dies are created from a full-scale model in order to duplicate these compound curved surfaces in sheet metal. The full-scale models used in aerospace vehicle manufacturing facilities are commonly called *mock-ups,* and the models used to transfer the compound curved surfaces are made by tool makers in the tooling department.

9.8 Developing Flat Patterns

Developing flat patterns can be done by bend deduction or setback. Figure 9.22 shows a type of sheet metal part that may be bent on a press brake. The flat-pattern part is bent on the brake, with the center-of-bend line (CBL) held on the bending die centerline. The machine's back gauge is set by the operator in order to form the part. If you study the figure closely, you can see how the dimensions progress: The bend deduction is drawn in, and the next dimension is taken from the end of the first bend deduction. The next dimension is then measured, the bend deduction is drawn in for that bend, and then the next dimension is taken from the end of the second bend deduction, etc. Notice that the second bend deduction is larger because of the larger radius of the second bend (0.16R).

9.9 Stiffening Sheet Metal Parts

On many sheet metal parts that have large areas, stiffening can be achieved by creasing the metal in an X configuration by means of brake bending. On certain parts where great stiffness and rigidity are required, a method called *beading* is employed. The beading is carried out at the same time as the part is being hydropressed, Marformed, or hard-die formed. See Fig. 9.23*b* and Chap. 8, "Tooling, Die Making, Molds, Jigs, and Fixtures," for more data on beading sheet metal parts.

Another method for stiffening the edge of a long sheet metal part is to hem or "Dutch bend" the edge, as shown in Fig. 9.23*a*. In aerospace and automotive sheet metal parts, flanged lightening holes are used as shown in Fig. 9.23*c*. The lightening hole makes the part not only lighter in weight but also more rigid. This method is used commonly in wing ribs, airframes, and gussets or brackets. The lightening hole need not be circular but can take any convenient shape as required by the application.

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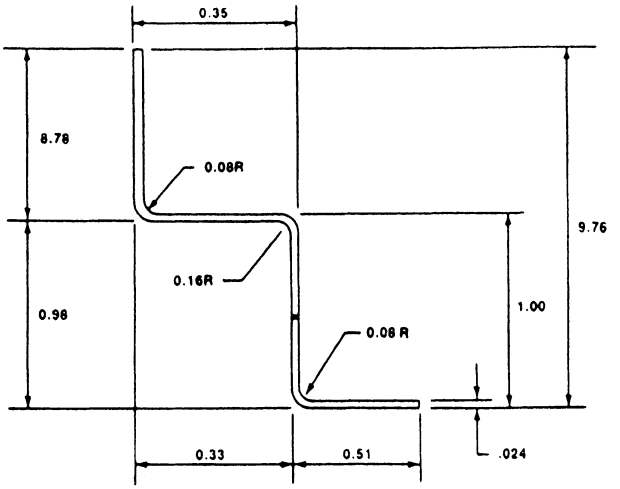

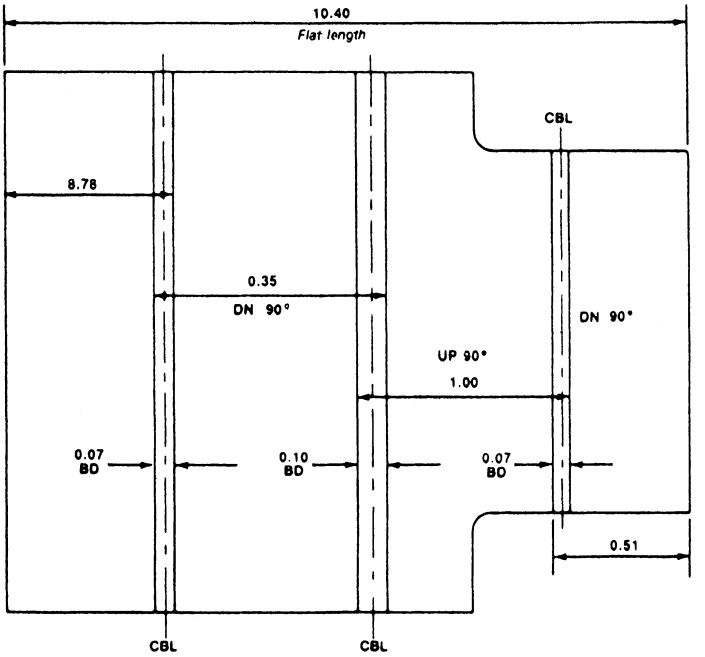

Figure 9.22 Layout of bent sheet metal by the bend deduction method.

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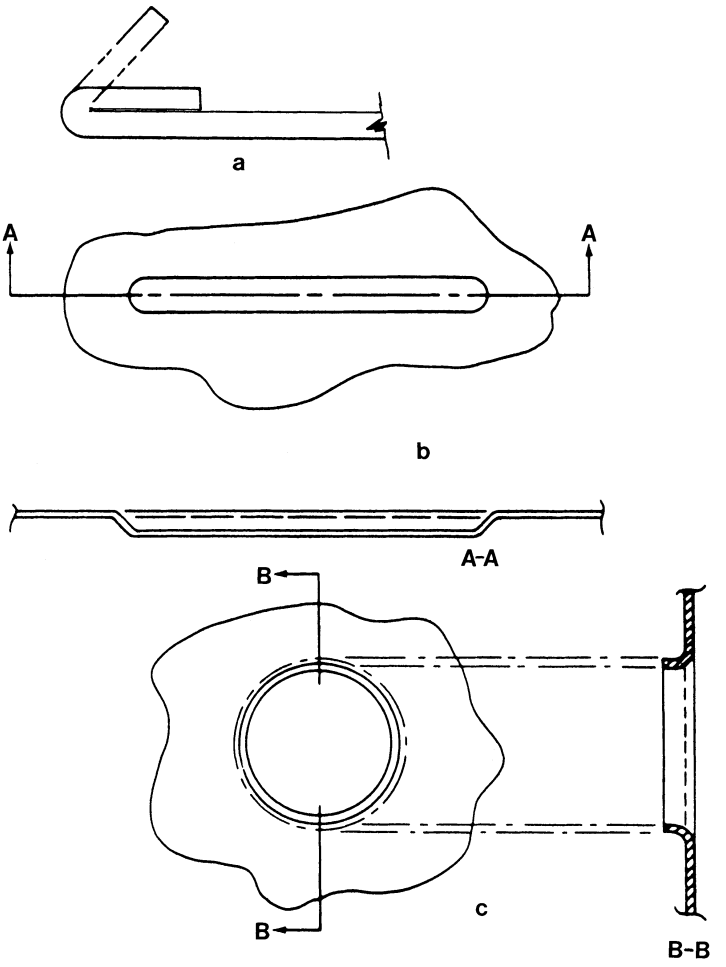

Figure 9.23 (*a*) A hemmed edge. (*b*) A stiffening bead. (*c*) A lightening hole.

9.10 Sheet Metal Faying Surfaces

Faying surfaces are those where two sheet metal parts come into contact with each other, such as the joining of a flange with a web section or the joining of two flanges. All faying surfaces should be primer painted or finished in some manner to prevent corrosion. A standard finish for many applications is zinc chromate primer.

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Other finishes include zinc plating, nickel plating, cadmium plating, chrome plating, etc. Since cadmium plating and plating solutions are toxic, zinc plating is used in its place where the application allows this. New designs should specify zinc or nickel in place of cadmium unless there is a specific technical reason for using cadmium.

9.11 Design Points for Sheet Metal Parts

- Do not specify flanges that are too narrow for the type of bending operation. That is, do not design a part with a 0.375-in flange width unless you have the equipment or dies to produce such a short flange on the press brake or other type of machine. Bottoming dies can enable the bending of such a flange in very light gauges up to no. 11 gauge.
- Do not specify gauges that are heavier than necessary for the function of the part. An exception to this rule is code specifications, such as for electrical switch-gear equipment, where a minimum of no. 11 gauge steel is specified for certain sections of the equipment whether it is structurally required or not. The heavy gauge limit in this application is for the prevention of the spread of fires between adjacent units if there is an electrical fault.
- Use proper edge distances for hardware components, keeping the flanges as narrow as practical with respect to their required rigidity or strength.
- Do not design a part that is impractical to bend on the type of machinery with which your operation is equipped.
- Keep brake-formed parts in a size range where the parts can be handled manually by the brake operators, unless your operation is equipped with automatic machinery or other special-handling equipment.
- When using hot-rolled steel sheets, use tolerances on your parts that are functionally related to the equipment used in your operation. That is, do not expect to hold dimensions to $\pm 1/64$ in when you are producing no. 11 gauge hot-rolled sheet metal parts on a press brake. Normal shop tolerance on general sheet metal parts is usually $\pm 1/32$ in for parts under 3 ft in length in both directions. One of the reasons that hot-rolled steel sheet metal parts between nos. 16 and 7 gauges need a generous tolerance is that the steel sheet metal thickness varies from sheet to sheet. This

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variation can reach ±½ a gauge step on a batch of steel of the same gauge. The variation of the gauge causes the flanges to be bent to different outside dimensions even though the back-gauge dimension is the same and is very apparent when more than two bends are made on the same part.

In high-speed, mass-production operations there is no remedy for this condition of variable thickness within the same gauge of hot-rolled steel sheet material except a favorable tolerance spread on the dimensions of the parts. Some of the larger companies specify the gauge-variation limits when they order steel sheet metal, but the mill order must be large in order to do this. These problems do not occur when using gauge-accurate cold-rolled steel sheets.

9.12 Typical Transitions and Developments

The following transitions and developments are the most common types, and learning or using them for reference will prove helpful in many industrial applications. Using the principles shown will enable you to apply these to many different variations or geometric forms. The principles shown and described in Sec. 9.7 will prove helpful in trying to understand and put into practice the transitions and developments shown in this section. Construction of the true-length diagrams is of particular importance.

9.12.1 To develop a truncated right cylinder

Refer to Fig. 9.24. The development of a cylinder is similar to the development of a prism. Draw two projections of the cylinder:

1. A normal view of a right section
2. A normal view of the elements

In rolling the cylinder out on a tangent plane, the base or right section, being perpendicular to the axis, will develop into a straight line. For convenience in drawing, divide the normal view of the base, shown here in the bottom view, into a number of equal parts by points that represent elements. These divisions should be spaced so that the chordal distances approximate the arc closely enough to make the stretch-out practically equal to the periphery of the base or right section.

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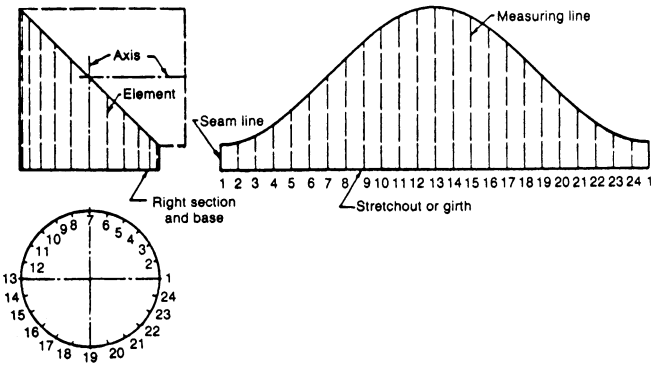

Figure 9.24 A truncated right cylinder.

Project these elements to the front view. Draw the stretch-out and measuring lines, the cylinder now being treated as a many-sided prism. Transfer the lengths of the elements in order, either by projection or by using dividers, and join the points thus found by a smooth curve. Sketch the curve in very lightly, freehand, before fitting the French curve or ship's curve to it. This development might be the pattern for one-half of a two-piece elbow.

Three-piece, four-piece, and five-piece elbows may be drawn similarly, as illustrated in Fig. 9.25. Since the base is symmetric, only one-half of it need be drawn. In these cases, the intermediate pieces such as *B*, *C*, and *D* are developed on a stretch-out line formed by laying off the perimeter of a right section. If the right section is taken through the middle of the piece, the stretch-out line becomes the center of the development. Evidently, any elbow could be cut from a single sheet without waste if the seams were made alternately on the long and short sides.

9.12.2 Conical connection between two cylindrical pipes

Refer to Fig. 9.26. The method used in drawing the pattern is the application of the development of an oblique cone. One-half the elliptical base is shown in true size in an auxiliary view (here attached to the front view). Find the true size of the base from its major and minor axes; divide it into a number of equal parts so that the sum of these chordal distances closely approximates the periphery of

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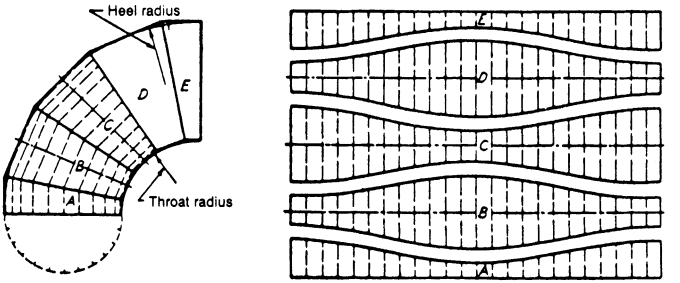

Figure 9.25 A five-piece elbow.

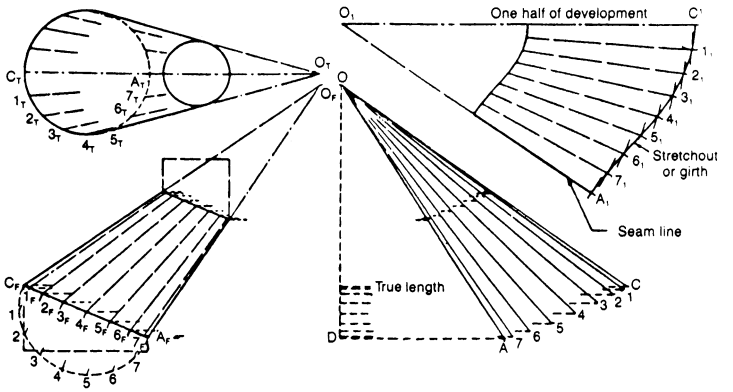

Figure 9.26 A conical connection between two cylinders.

the curve. Project these points to the front and top views. Draw the elements in each view through these points, and find the vertex O by extending the contour elements until they intersect.

The true length of each element is found by using the vertical distance between its ends as the vertical leg of the diagram and its horizontal projection as the other leg. As each true length from vertex to base is found, project the upper end of the intercept horizontally across from the front view to the true length of the corresponding element to find the true length of the intercept. The development is drawn by laying out each triangle in turn, from vertex to base, starting on the centerline O_1C_1, and then measuring on each element its intercept length. Draw smooth curves through these points to complete the pattern.

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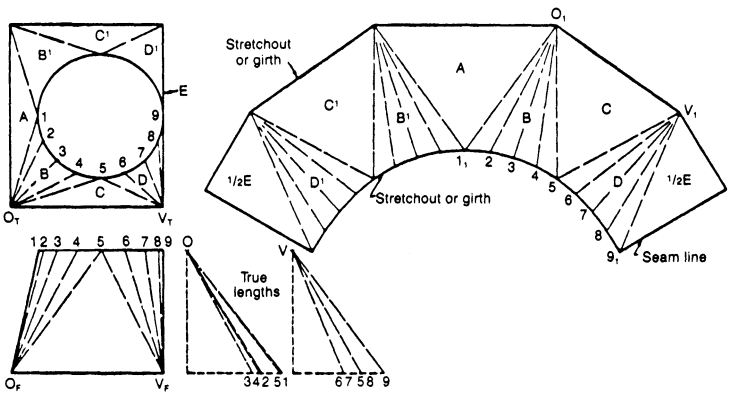

Figure 9.27 A transition piece.

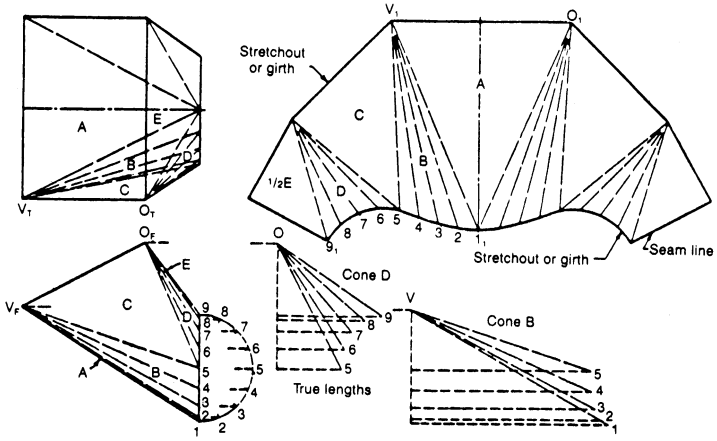

Figure 9.28 A transition piece.

9.12.3 To develop transition pieces

Refer to Figs. 9.27 and 9.28. Transitions are used to connect pipes or openings of different shapes or cross sections. Figure 9.27, showing a transition piece for connecting a round pipe and a rectangular pipe, is typical. These pieces are always developed by triangulation. The piece shown in the figure is evidently made up of four triangu-

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lar planes whose bases are the sides of the rectangle and four parts of oblique cones whose common bases are arcs of the circle and whose vertices are at the corners of the rectangle. To develop the piece, make a true-length diagram as shown in Sec. 9.12.2. The true length of O_1 being found, all the sides of triangle A will be known. Attach the developments of cones B and B^1 and then those of triangle C and C^1 and so on.

Figure 9.28 is another transition piece joining a rectangle to a circular pipe whose axes are not parallel. By using a partial right-side view of the round opening, the divisions of the bases of the oblique cones can be found. (Since the object is symmetric, only one-half the opening need be divided.) The true lengths of the elements are obtained as shown in Fig. 9.27.

9.12.4 Triangulation of warped surfaces

The approximate development of a warped surface is made by dividing it into a number of narrow quadrilaterals and then splitting each of these into two triangles by a diagonal line, which is assumed to be a straight line, although it is really a curve. Figure 9.29 shows a warped transition piece that connects on ovular (upper) pipe with a right-circular cylindrical pipe (lower). Find the true size of one-half the elliptical base by rotating it until horizontal about an axis through 1, when its true shape will be seen. The major axis is $1 - 7_R$, and the minor axis through 4_R will be equal to the diameter of the lower pipe.

Divide the semiellipse into a sufficient number of equal parts, and project these to the top and front views. Divide the top semicircle into the same number of equal parts, and connect similar points on each end, thus dividing the surface into approximate quadrilaterals. Cut each into two triangles by a diagonal. On true-length diagrams, find the lengths of the elements and the diagonals, and draw the development by constructing the true sizes of the triangles in regular order.

9.12.5 Angled, flanged corner notching procedures and calculations

Sheet metal parts sometimes have angled flanges that must be bent up for an exact angular fit. Figure 9.30*a* shows a typical sheet metal part with 45° bent-up flanges. In order to lay out the corner

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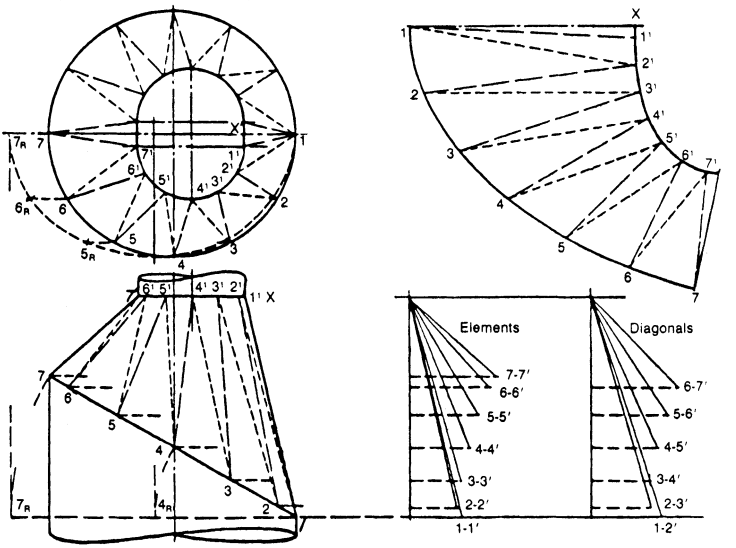

Figure 9.29 A warped transition piece.

notch angle for this type of part, you may use computer programs such as AutoCad to find the correct dimensions and angular cut at the corners, or you may calculate the corner angular cut by using trigonometry. To calculate the corner angular notch trigonometrically, proceed as follows: From Fig. 9.30*a*, sketch the flat-pattern edges and true lengths as shown in Fig. 9.30*b*, forming a triangle *ABC,* which may now be solved using the law of cosines first to find side b and then the law of sines to determine the corner half-notch angle, angle C.

The triangle ABC begins with known dimensions: $a = 4$, angle $B = 45°$, and $c = 0.828$. This is a triangle where you know two sides and the included angle B. You will need to first find side b using the law of cosines as follows:

$$b^2 = a^2 + c^2 - 2ac \cos B$$

$$b^2 = (4)^2 + (0.828)^2 - 2 \times 4 \times 0.828 \times 0.707 \qquad \text{by the law of cosines}$$

$$b^2 = 12.00242$$

$$b = 3.464$$

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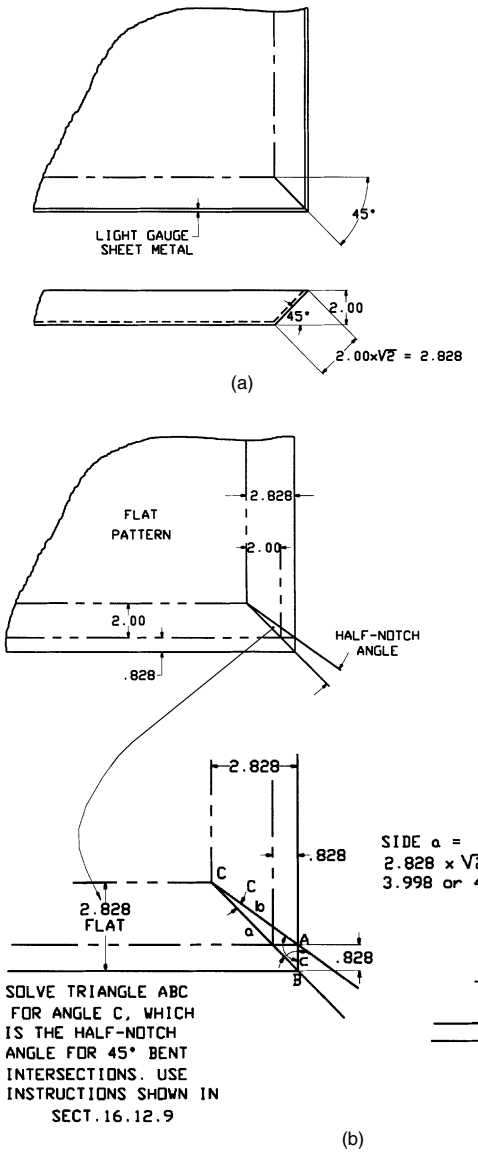

Figure 9.30 (*a*) Developing angular flange notching. (*b*) Flat-pattern development of angular bent-flange corner notches.

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Then find angle C using the law of sines:

$$\sin B / b = \sin C / c$$

$$\frac{\sin B}{3.464} = \frac{\sin C}{0.828}$$

$$\frac{\sin 45}{3.464} = \frac{\sin C}{0.828}$$

Solving for sin C, we have

$$\sin C = 0.16899$$

$$\arcsin 0.16899 = 9.729°$$

Therefore, the notch angle $= 2 \times 9.729° = 19.458°$.

This procedure may be used for determining the notch angle for flanges bent on any angle. The angle just given as 19.458° is valid for any flange length as long as the bent-up angle is 45°. This notch angle will increase as bent-up flanges approach 90° until the angle of notch becomes 90° for a bent-up angle of 90°.

Note: The triangle *ABC* shown in this example is actually the overlap angle of the metal flanges as they become bent-up 45°, which must be removed as the corner notch. On thicker sheet metal such as no. 16 through no. 7 gauge, you should do measurements and calculations from the inside mold line (IML) of the flat-pattern sheet metal. Also, the flange height, shown as 2 in in Fig. 9.30*a*, could have been 1 in or any other dimension in order to do the calculations. Thus the corner notch angle is a constant angle for every given bent-up angle; i.e., the angular notch for all 45° bent-up flanges is always 19.458°. It will always be a different constant angle for every different bent-up flange angle.

9.13 Sheet Metal Fabrication Practices

Figures 9.31 through 9.38 illustrate some of the methods used in sheet metal design and fabrication practices. A detailed description of the figures follows: Figure 9.31 shows the accepted methods of relieving the corner stresses and deformation that occur when sheet metal flanges meet at a 90° corner. Circular punch, oblong punch, and saw cuts are illustrated. Figure 9.32 shows that a sheet metal angle may be offset (joggled) to fit over another sheet metal part

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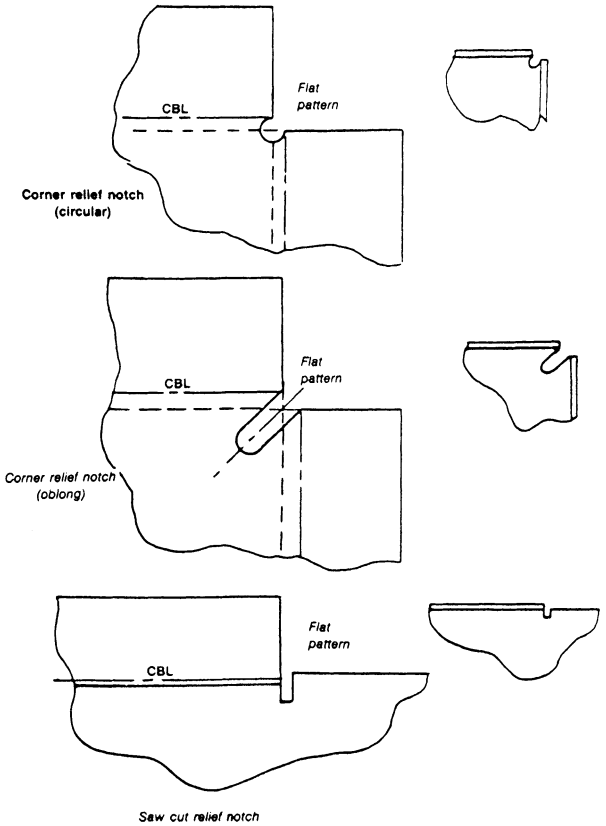

Figure 9.31 Sheet metal corners.

(common practice in the aerospace industry). Corners are formed and fastened by welding directly or with gusset plates.

In Fig. 9.33, a partially closed sheet metal part that normally would be roll-formed is produced on a press brake using this sequence. The outer flanges are bent; then the center is bent to form a W section; finally, the section is completed with a flattening die. Figure 9.34 shows that a return flange on a sheet metal part is possible only when a "gooseneck" die is used in the operation. This forming operation is normally done in a press brake.

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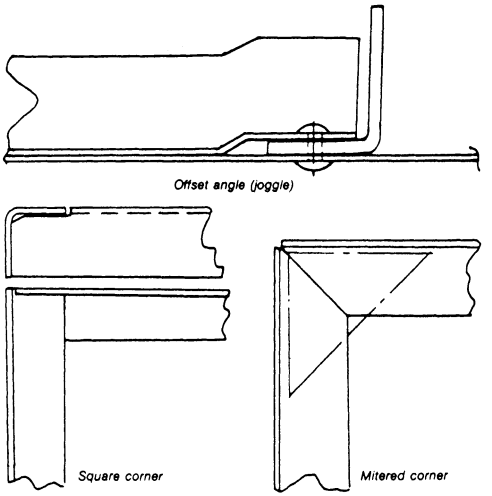

Figure 9.32 Sheet metal intersections.

A sheet metal stake is shown at left in Fig. 9.35. Stakes are used as stops as well as for spring anchors. An integral flange, at right in Fig. 9.35, is produced in the web of a sheet metal part. The sheet metal must first be die-punched prior to the bending operation.

The punch tap is an economical method for producing tapped holes in sheet metal parts. The hole is first punched and extruded by the same die and then tapped with the appropriate thread (Fig. 9.36). The maximum practical size of a punch-tapped hole is generally 0.375-16 in no. 11 gauge sheet steel. Figure 9.37*a* shows the common corner break or stiffening notch that is formed in the heel section of a sheet metal angle. These simple metal deformation methods add a great amount of strength and stiffness to light-gauge sheet metal parts. Figure 9.38 illustrates some of the common methods of applying gaskets to sheet metal doors and the sheet metal configurations required in these gasketing methods.

9.14 Light-Gauge Sheet Metal Structural Forms: Dimensions and Strengths

Tables 9.1 through 9.11 show the complete dimensions and properties of sheet metal structural shapes that have a wide range of uses in industrial applications. Light-gauge cold-formed steel sheet

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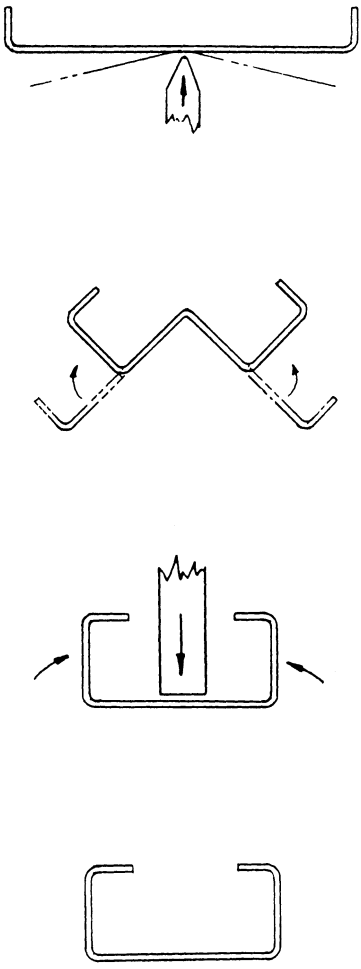

Figure 9.33 Press brake forming a partially closed section.

metal shapes have a high strength-to-weight ratio and are used in countless applications. The tables were extracted from the *Light Gauge Cold-Formed Steel Design Manual*, which was produced by the American Iron and Steel Institute (AISI). The latest edition of this engineering design manual may be obtained from the AISI (see Chap. 16, "Societies, Associations, Institutes, and Specification Authorities," for the address).

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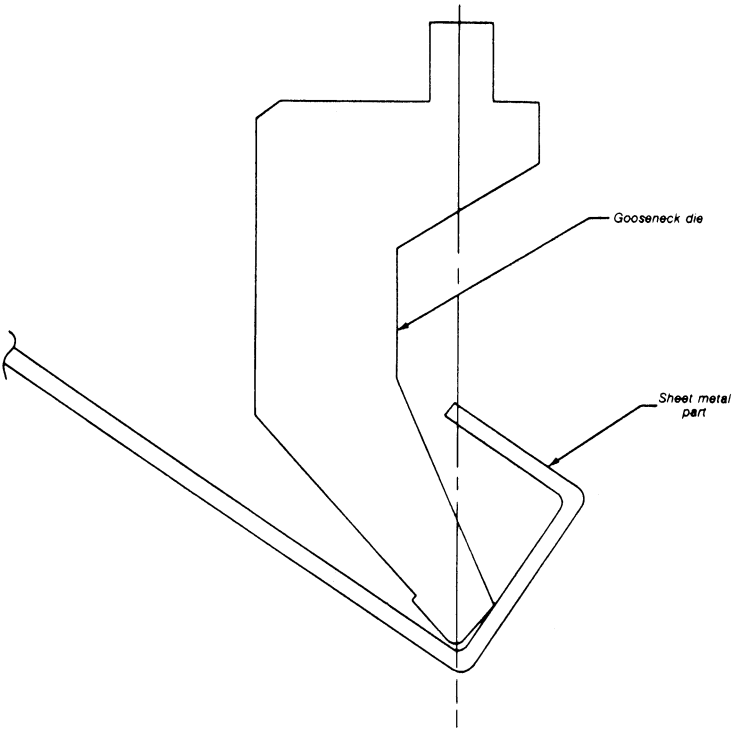

Figure 9.34 Return flange bending.

In the tables, the properties about the *xx* and *yy* axes are most important from a design standpoint for calculating the simple strength capabilities of each particular shape. The following symbolism is defined in the tables:

$I_{x,y}$ = moment of inertia, in^4 (about the *xx* or *yy* axes)

$S_{x,y}$ = section modulus, in^3 (about the *xx* or *yy* axes)

$r_{x,y}$ = radius of gyration, in (about the *xx* or *yy* axes)

x = location of centroid, in (center of gravity of the section)

The equations for calculating the deflection under a given load and the maximum stress imposed on the member for various conditions of loading may be found in other chapters of this *Handbook*. Also, column-bending calculations may be found herein (see Index).

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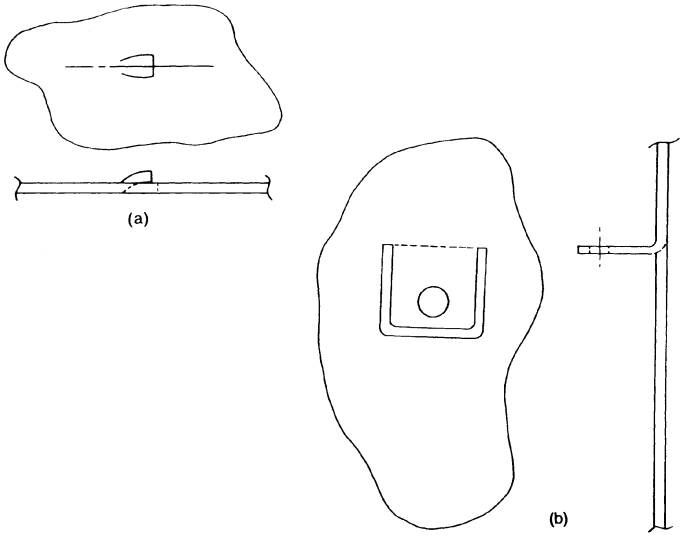

Figure 9.35 Stakes and integral flanges.

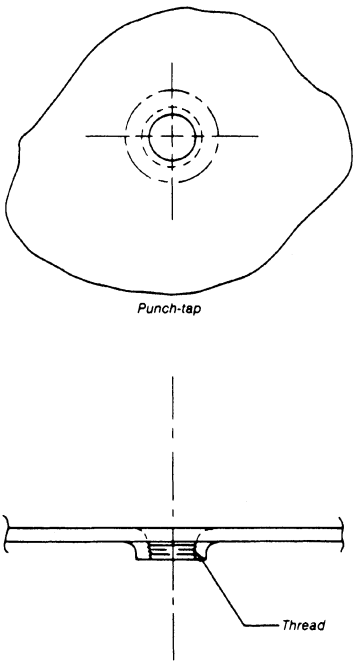

Figure 9.36 A punch-tapped hole.

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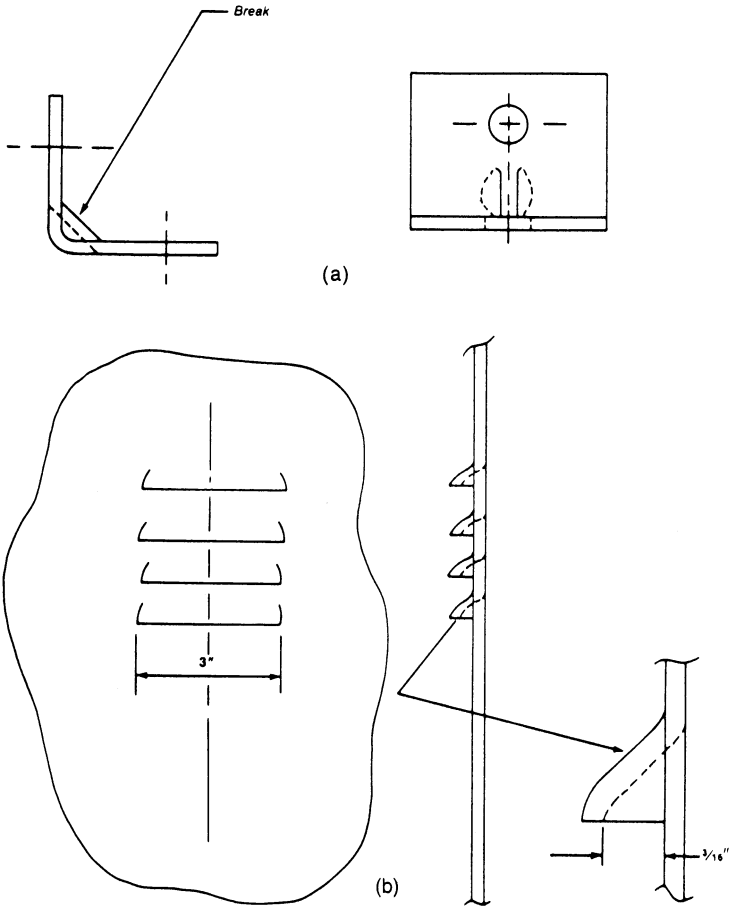

Figure 9.37 (*a*) Corner break. (*b*) Louvers (air vents).

9.15 The Effects of Cold-Working Steel Sheet Metal

It has long been known that any cold working, such as cold stretching, bending, twisting, etc., affects the mechanical properties of steel. Generally, such operations produce strain hardening; i.e., they increase the yield strength and, to a lesser degree, the ultimate tensile strength of steels while decreasing the ductility. Cold working of one sort or another occurs in all cold-forming operations, such as roll forming or forming in press brakes. The properties of the cold-

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Sheet Metal Practices and Layout

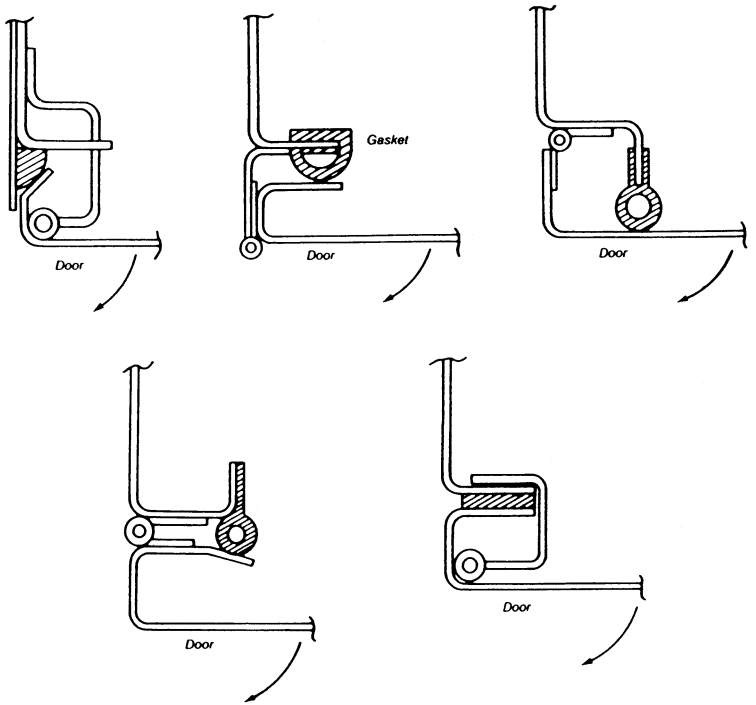

Figure 9.38 Methods of applying door gaskets.

worked parts thus are different from the metal prior to the cold-forming operations. The effects of cold forming depend strongly on the details of the particular cold-forming process. The effects of cold forming are also much more evident in the bent corners than in the flat sections. Metallurgically different kinds of structural carbon steels react differently to the same cold-forming process. The actual effects of any cold-forming operation on sheet steels are, of course, of an extremely complex nature. Unusual or excessive cold working of structural sheet steel may render the formed section unsuitable for a particular application. In other words, the cold-worked section may be weakened by excessive cold-forming operations.

Bending and buckling of sheet metal sections used as columns and bracing or support beams may be calculated by referring to the chapters of this *Handbook* that cover engineering subjects (also see the Index).

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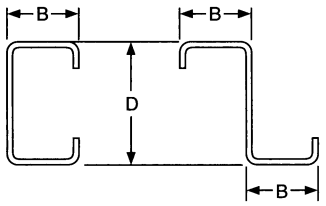
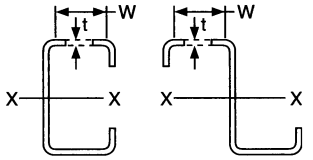
TABLE 9.1 Channel or Zee with Stiffened Flanges



Effective section for beam strength about the x-x axis where w/t of compression flange exceeds 28.4 for f_b = 20,000 psi and 23.2 for f_b = 30,000 psi.



Nominal Size $D \times B$	Gauge	t	Wt./ft	Beam strength: Effective S_x [or] f_b = 20,000 psi	Beam strength: Effective S_x [or] f_b = 30,000 psi	Area [or]	Properties of full section: Axis xx [or] I_x	Axis xx [or] S_x	Axis xx [or] r_x	Axis yy [ ] I_y	Axis yy [ ] S_y	Axis yy [ ] r_y	Axis yy [ ] x
in	No.	in	lb	in^3	in^3	in^2	in^4	in^3	in	in^4	in^3	in	in
12 × 3½	10	0.135	9.42	9.37	9.37	2.70	56.2	9.37	4.56	4.03	1.55	1.22	0.910
	12	0.105	7.31	7.31	7.22	2.10	43.8	7.31	4.57	3.09	1.18	1.21	0.883
10 × 3½	10	0.135	8.48	7.30	7.30	2.43	36.5	7.30	3.87	3.81	1.53	1.25	1.00
	12	0.105	6.57	5.70	5.64	1.89	28.5	5.70	3.89	2.93	1.16	1.25	0.975
	14	0.075	4.67	3.90	3.72	1.34	20.5	4.10	3.91	2.02	0.783	1.23	0.926
9 × 3¼	10	0.135	7.77	6.04	6.04	2.23	27.2	6.04	3.49	3.08	1.35	1.17	0.965
	12	0.105	5.95	4.66	4.65	1.71	21.0	4.66	3.50	2.26	0.965	1.15	0.910
	14	0.075	4.28	3.29	3.15	1.23	15.3	3.40	3.53	1.63	0.689	1.15	0.888
	16	0.060	3.40	2.49	2.36	0.975	12.2	2.70	3.53	1.26	0.527	1.14	0.859
8 × 3	10	0.135	6.97	4.83	4.83	2.00	19.3	4.83	3.11	2.33	1.11	1.08	0.901
	12	0.105	5.40	3.78	3.78	1.55	15.1	3.78	3.12	1.79	0.840	1.07	0.873
	14	0.075	3.89	2.72	2.62	1.12	11.1	2.76	3.15	1.29	0.600	1.08	0.851
	16	0.060	3.08	2.06	1.95	0.885	8.79	2.20	3.15	0.997	0.458	1.06	0.822

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7 × 2¾	10	0.135	6.17	3.75	3.75	1.77	13.1	3.75	2.72	1.71	0.893	0.982	0.837
	12	0.105	4.86	2.98	2.98	1.39	10.4	2.98	2.74	1.38	0.723	0.996	0.837
	14	0.075	3.50	2.18	2.11	1.00	7.66	2.19	2.76	1.00	0.517	0.999	0.815
	16	0.060	2.77	1.67	1.59	0.795	6.10	1.74	2.77	0.773	0.393	0.986	0.786
6 × 2½	10	0.135	5.37	2.81	2.81	1.54	8.42	2.81	2.34	1.21	0.700	0.885	0.774
	12	0.105	4.23	2.24	2.24	1.21	6.72	2.24	2.35	0.983	0.570	0.900	0.774
	14	0.075	3.10	1.68	1.65	0.891	5.04	1.68	2.38	0.756	0.440	0.921	0.780
	16	0.060	2.46	1.31	1.26	0.705	4.01	1.34	2.39	0.583	0.333	0.910	0.751
5 × 2	10	0.135	4.43	1.88	1.88	1.27	4.69	1.88	1.92	0.651	0.480	0.715	0.644
	12	0.105	3.50	1.51	1.51	1.00	3.76	1.51	1.94	0.534	0.394	0.729	0.643
	14	0.075	2.53	1.12	1.12	0.726	2.80	1.12	1.96	0.390	0.283	0.733	0.622
	16	0.060	2.00	0.890	0.881	0.573	2.23	0.891	1.97	0.298	0.212	0.721	0.594
	18	0.048	1.61	0.706	0.681	0.461	1.80	0.722	1.98	0.244	0.173	0.727	0.594
4 × 2	10	0.135	3.96	1.38	1.38	1.14	2.76	1.38	1.56	0.601	0.466	0.727	0.712
	12	0.105	3.14	1.11	1.11	0.900	2.22	1.11	1.57	0.493	0.383	0.740	0.712
	14	0.075	2.27	0.832	0.832	0.651	1.67	0.832	1.60	0.361	0.276	0.745	0.689
	16	0.060	1.79	0.665	0.655	0.513	1.33	0.665	1.61	0.277	0.206	0.735	0.660
	18	0.048	1.44	0.529	0.508	0.413	1.08	0.540	1.62	0.226	0.169	0.740	0.660
3½ × 2	10	0.135	3.73	1.15	1.15	1.07	2.01	1.15	1.37	0.571	0.458	0.730	0.753
	12	0.105	2.95	0.927	0.927	0.847	1.62	0.927	1.38	0.469	0.376	0.744	0.753
	14	0.075	2.14	0.699	0.699	0.613	1.22	0.699	1.41	0.344	0.271	0.750	0.729
	16	0.060	1.68	0.559	0.551	0.483	0.979	0.560	1.42	0.264	0.203	0.740	0.699
	18	0.048	1.36	0.444	0.426	0.389	0.795	0.455	1.43	0.216	0.166	0.745	0.699
3 × 1¾	12	0.105	2.59	0.679	0.679	0.742	1.02	0.679	1.17	0.319	0.300	0.655	0.689
	14	0.075	1.82	0.509	0.509	0.523	0.764	0.509	1.21	0.219	0.196	0.647	0.635
	16	0.060	1.47	0.416	0.416	0.423	0.624	0.416	1.22	0.181	0.162	0.654	0.635
	18	0.048	1.16	0.331	0.322	0.331	0.498	0.332	1.23	0.137	0.119	0.642	0.604

NOTE: The effective section moduli in bending about the *yy* axis have not been tabulated. When one of the webs acts as a compression flange, the section modulus should be calculated on the basis of its effective width as provided in Section 2.3 of the Design Specification. When the web acts as a tension flange, the section modulus of the full section is effective. For all of the sections listed in this table the moment of inertia I_x of the full section may be used in deflection calculations without appreciable error.

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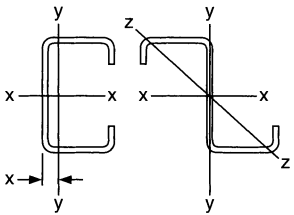
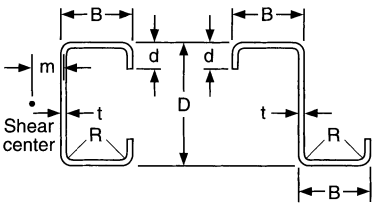
TABLE 9.1 Channel or Zee with Stiffened Flanges (*Continued*)





Properties of full section (cont'd)					Column factor Q ⊏ or ⊐		Dimensions of sections ⊏ or ⊐							
Axis *yy* ⊐			Axis *zz* ⊐	Product of inertia ⊐										
I_y	S_y	r_y	*r* min.	I_{xy}	f_b = 20,000 psi	f_b = 30,000 psi	*D*	*B*	*d*	*t*	*R*	*m*	Gauge	Size *D* × *B*
in^4	in^3	in	in	in^4			in	in	in	in	in	in	No.	in
5.94	1.73	1.48	1.00	13.1	0.751	0.703	12.0	3.50	1.0	0.135	3/16	1.41	10	12 × 3½
4.54	1.32	1.47	1.00	10.1	0.689	0.640	12.0	3.50	0.9	0.105	3/16	1.41	12	
5.94	1.73	1.56	1.01	10.8	0.819	0.770	10.0	3.50	1.0	0.135	3/16	1.50	10	10 × 3½
4.54	1.32	1.55	1.01	8.36	0.756	0.705	10.0	3.50	0.9	0.105	3/16	1.49	12	
3.07	0.888	1.51	0.992	5.80	0.634	0.567	10.0	3.50	0.7	0.075	3/32	1.43	14	
4.87	1.53	1.48	0.947	8.51	0.852	0.803	9.0	3.25	1.0	0.135	3/16	1.43	10	9 × 3¼
3.51	1.10	1.43	0.925	6.33	0.785	0.737	9.0	3.25	0.8	0.105	3/16	1.38	12	

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2.52	0.783	1.43	0.928	4.56	0.674	0.607	9.0	3.25	0.7	0.075	3/32	1.35	14
1.93	0.599	1.41	0.916	3.55	0.590	0.522	9.0	3.25	0.6	0.060	3/32	1.32	16
													8×3
3.72	1.27	1.36	0.864	6.29	0.887	0.837	8.0	3.00	0.9	0.135	3/16	1.32	10
2.83	0.960	1.35	0.860	4.85	0.821	0.774	8.0	3.00	0.8	0.105	3/16	1.31	12
2.03	0.685	1.35	0.863	3.50	0.719	0.653	8.0	3.00	0.7	0.075	3/32	1.27	14
1.55	0.523	1.32	0.851	2.73	0.635	0.565	8.0	3.00	0.6	0.060	3/32	1.25	16
													$7 \times 2\frac{3}{4}$
2.76	1.03	1.25	0.782	4.49	0.924	0.876	7.0	2.75	0.8	0.135	3/16	1.22	10
2.24	0.830	1.27	0.793	3.61	0.861	0.814	7.0	2.75	0.8	0.105	3/16	1.24	12
1.61	0.593	1.27	0.796	2.61	0.764	0.701	7.0	2.75	0.7	0.075	3/32	1.20	14
1.23	0.451	1.24	0.785	2.03	0.686	0.615	7.0	2.75	0.6	0.060	3/32	1.18	16
													$6 \times 2\frac{1}{2}$
1.98	0.813	1.13	0.699	3.06	0.962	0.919	6.0	2.50	0.7	0.135	3/16	1.12	10
1.62	0.660	1.15	0.710	2.48	0.905	0.858	6.0	2.50	0.7	0.105	3/16	1.14	12
1.25	0.507	1.18	0.729	1.88	0.815	0.759	6.0	2.50	0.7	0.075	3/32	1.13	14
0.950	0.385	1.16	0.718	1.46	0.744	0.674	6.0	2.50	0.6	0.060	3/32	1.11	16
													5×2
1.07	0.555	0.919	0.570	1.68	0.994	0.964	5.0	2.00	0.7	0.135	3/16	0.913	10
0.885	0.454	0.939	0.580	1.37	0.951	0.907	5.0	2.00	0.7	0.105	3/16	0.936	12
0.638	0.325	0.938	0.583	0.998	0.858	0.811	5.0	2.00	0.6	0.075	3/32	0.900	14
0.480	0.244	0.915	0.573	0.772	0.801	0.745	5.0	2.00	0.5	0.060	3/32	0.878	16
0.393	0.199	0.924	0.577	0.629	0.737	0.670	5.0	2.00	0.5	0.048	3/32	0.890	18
													4×2
1.07	0.555	0.971	0.558	1.31	1.000	0.998	4.0	2.00	0.7	0.135	3/16	0.976	10
0.885	0.454	0.992	0.568	1.07	0.994	0.968	4.0	2.00	0.7	0.105	3/16	0.998	12
0.638	0.325	0.990	0.571	0.786	0.926	0.885	4.0	2.00	0.6	0.075	3/32	0.954	14
0.480	0.244	0.967	0.561	0.610	0.875	0.821	4.0	2.00	0.5	0.060	3/32	0.934	16
0.393	0.199	0.976	0.565	0.498	0.810	0.738	4.0	2.00	0.5	0.048	3/32	0.942	18
													$3\frac{1}{2} \times 2$
1.07	0.555	1.00	0.544	1.13	1.000	1.000	3.5	2.00	0.7	0.135	3/16	1.01	10
0.885	0.454	1.02	0.553	0.923	1.000	0.991	3.5	2.00	0.7	0.105	3/16	1.03	12
0.638	0.325	1.02	0.556	0.681	0.959	0.922	3.5	2.00	0.6	0.075	3/32	0.992	14

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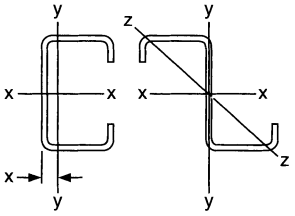
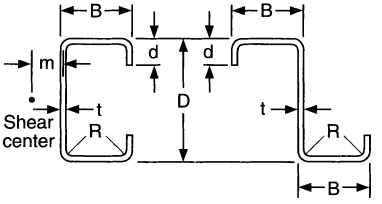
TABLE 9.1 Channel or Zee with Stiffened Flanges (*Continued*)





Properties of full section (cont'd)							Dimensions of sections							
Axis *yy*			Axis *zz*	Product of inertia	Column factor Q									
⌐			⌐	⌐	[or ⌐		[or ⌐							
I_y	S_y	r_y	*r* min.	I_{xy}	f_b = 20,000	f_b = 30,000	*D*	*B*	*d*	*t*	*R*	*m*	Gauge	Size *D* × *B*
in^4	in^3	in	in	in^4	psi	psi	in	in	in	in	in	in	No.	in
0.480	0.244	0.997	0.547	0.529	0.914	0.861	3.5	2.00	0.5	0.060	3/32	0.966	16	
0.393	0.199	1.01	0.551	0.432	0.851	0.779	3.5	2.00	0.5	0.048	3/32	0.972	18	
0.619	0.365	0.913	0.488	0.610	1.000	1.000	3.0	1.75	0.7	0.105	3/16	0.932	12	3 × 1¾
0.406	0.239	0.881	0.477	0.430	0.985	0.954	3.0	1.75	0.5	0.075	3/32	0.860	14	
0.336	0.195	0.891	0.482	0.354	0.949	0.910	3.0	1.75	0.5	0.060	3/32	0.867	16	
0.248	0.144	0.865	0.471	0.272	0.900	0.840	3.0	1.75	0.4	0.048	3/32	0.841	18	

DIMENSIONS: Equipment and forming practices vary with different manufacturers, resulting in minor variations in some of these dimensions. These minor variations do not affect the published properties. Consult the manufacturer for actual weight per foot and actual dimensions.

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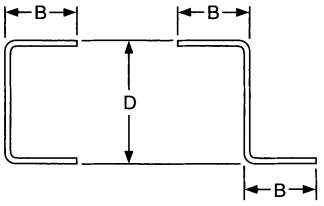
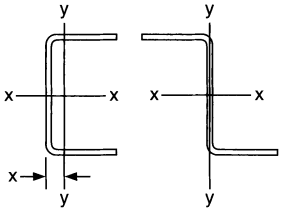
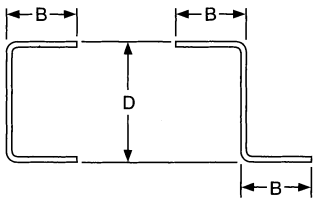
TABLE 9.2 Channel or Zee with Unstiffened Flanges

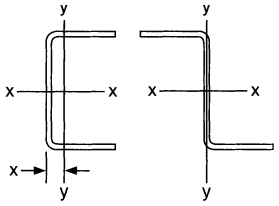




Nominal Size $D \times B$	Nominal Gauge	t	Wt./ft	Area [or ⌐	Properties of full section: Axis xx [or ⌐ I_x	Axis xx [or ⌐ S_x	Axis xx [or ⌐ r_x	Axis yy [I_y	Axis yy [S_y	Axis yy [r_y	Axis yy [x	Axis yy ⌐ I_y	Axis yy ⌐ S_y	Axis yy ⌐ r_y
in	No.	in	lb	in^2	in^4	in^3	in	in^4	in^3	in	in	in^4	in^3	in
8 × 2	10	0.135	5.38	1.55	12.9	3.24	2.89	0.465	0.293	0.548	0.383	0.621	0.327	0.634
	12	0.105	4.23	1.21	10.3	2.57	2.91	0.379	0.236	0.559	0.376	0.510	0.263	0.648
	14	0.075	3.08	0.884	7.66	1.91	2.94	0.294	0.178	0.577	0.373	0.396	0.199	0.669
	16	0.060	2.44	0.699	6.02	1.50	2.93	0.211	0.132	0.549	0.343	0.279	0.146	0.632
7 × 1½	10	0.135	4.39	1.26	7.54	2.15	2.45	0.170	0.148	0.368	0.260	0.214	0.161	0.413
	12	0.105	3.50	1.00	6.18	1.77	2.48	0.160	0.131	0.399	0.268	0.209	0.145	0.456
	14	0.075	2.53	0.725	4.54	1.30	2.50	0.113	0.0930	0.395	0.248	0.144	0.101	0.446
	16	0.060	1.99	0.572	3.54	1.01	2.49	0.077	0.0669	0.368	0.221	0.985	0.0730	0.415
6 × 1½	10	0.135	3.91	1.12	5.12	1.70	2.13	0.164	0.146	0.382	0.283	0.214	0.161	0.437
	12	0.105	3.13	0.898	4.22	1.40	2.17	0.155	0.130	0.415	0.293	0.209	0.145	0.482
	14	0.075	2.26	0.650	3.10	1.03	2.19	0.109	0.0918	0.410	0.272	0.144	0.101	0.471
	16	0.060	1.78	0.512	2.42	0.806	2.17	0.075	0.0660	0.383	0.243	0.0985	0.0730	0.439
	18	0.048	1.43	0.409	1.94	0.646	2.18	0.059	0.0519	0.378	0.234	0.0764	0.0572	0.432
5 × 1¼	12	0.105	2.58	0.741	2.38	0.953	1.79	0.087	0.0884	0.343	0.252	0.118	0.0991	0.398
	14	0.075	1.84	0.528	1.71	0.683	1.80	0.053	0.0563	0.316	0.214	0.0690	0.0620	0.362

TABLE 9.2 Channel or Zee with Unstiffened Flanges (*Continued*)





Nominal				Properties of full section										
				Area	Axis *xx*			Axis *yy*						
					[or ⌋			[				⌋		
Size $D \times B$	Gauge	t	Wt./ft	[or ⌋	I_x	S_x	r_x	I_y	S_y	r_y	x	I_y	S_y	r_y
in	No.	in	lb	in^2	in^4	in^3	in	in^4	in^3	in	in	in^4	in^3	in
	16	0.060	1.47	0.422	1.37	0.547	1.80	0.041	0.0439	0.311	0.202	0.0533	0.0485	0.355
	18	0.048	1.15	0.331	1.06	0.423	1.79	0.027	0.0307	0.284	0.176	0.0346	0.0337	0.323
4 × 1⅛	12	0.105	2.17	0.623	1.33	0.663	1.46	0.071	0.0779	0.337	0.265	0.0981	0.0878	0.397
	14	0.075	1.61	0.462	1.02	0.512	1.49	0.058	0.0611	0.355	0.262	0.0807	0.0689	0.418
	16	0.060	1.26	0.362	0.792	0.396	1.48	0.039	0.0430	0.327	0.230	0.0533	0.0485	0.384
	18	0.048	1.01	0.289	0.635	0.318	1.48	0.030	0.0337	0.322	0.220	0.0410	0.0378	0.377
3 × 1⅛	12	0.105	1.80	0.518	0.658	0.439	1.13	0.065	0.0750	0.354	0.308	0.0980	0.0877	0.435
	14	0.075	1.35	0.387	0.515	0.344	1.15	0.054	0.0590	0.372	0.306	0.0807	0.0688	0.457
	16	0.060	1.05	0.302	0.398	0.265	1.15	0.036	0.0416	0.344	0.270	0.0533	0.0485	0.420
	18	0.048	0.841	0.241	0.319	0.213	1.15	0.028	0.0326	0.339	0.259	0.0410	0.0378	0.412
2 × 1⅛	12	0.105	1.44	0.413	0.250	0.250	0.779	0.056	0.0702	0.369	0.374	0.0979	0.0876	0.487
	14	0.075	1.09	0.312	0.200	0.200	0.800	0.047	0.0556	0.387	0.370	0.0807	0.0688	0.509
	16	0.060	0.843	0.242	0.154	0.154	0.799	0.031	0.0392	0.360	0.330	0.0533	0.0484	0.469
	18	0.048	0.673	0.193	0.124	0.124	0.802	0.024	0.0308	0.356	0.318	0.0410	0.0378	0.461

NOTE: The effective section moduli in bending about the *yy* axis have not been tabulated. When one of the webs acts as a compression flange, the section modulus should be calculated on the basis of its effective width as provided in Section 2.3 of the Design Specification. When the web acts as a tension flange, the section modulus of the full section is effective.

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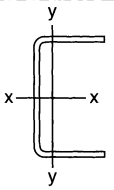

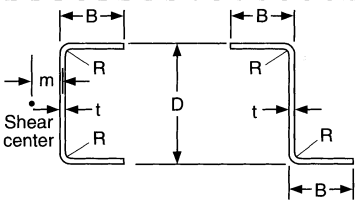

Properties of full section (cont'd)		Allowable beam stress f_c		Column factor Q		Dimensions of sections						
Axis *zz*	Product of inertia					⌐ or ⌐						
⌐	⌐											
r min.	I_{xy}	[or ⌐		[or ⌐		*D*	*B*	*t*	*R*	*m*	Gauge	Size *D* × *B*
in	in	f_b = 20,000 psi	f_b = 30,000 psi	f_b = 20,000 psi	f_b = 30,000 psi	in	in	in	in	in	No.	in
0.461	1.92	18,960	27,490	0.817	0.736	8.0	1.97	0.135	3/16	0.531	10	8 × 2
0.470	1.56	17,100	22,980			8.0	1.99	0.105	3/16	0.552	12	
0.486	1.18	13,040	13,150			8.0	2.03	0.075	3/32	0.581	14	
0.463	0.869	11,610	11,610			8.0	1.94	0.060	3/32	0.550	16	
0.312	0.825	20,000	30,000	0.893	0.825	7.0	1.40	0.135	3/16	0.329	10	7 × 1½
0.341	0.750	19,340	28,400			7.0	1.49	0.105	3/16	0.376	12	
0.336	0.526	16,610	21,790			7.0	1.46	0.075	3/32	0.376	14	
0.316	0.380	15,090	18,130			7.0	1.38	0.060	3/32	0.350	16	
0.320	0.705	20,000	30,000	0.948	0.889	6.0	1.40	0.135	3/16	0.353	10	6 × 1½
0.348	0.641	19,340	28,400	0.849	0.774	6.0	1.49	0.105	3/16	0.402	12	
0.345	0.450	16,610	21,790			6.0	1.46	0.075	3/32	0.402	14	
0.324	0.325	15,090	18,130			6.0	1.38	0.060	3/32	0.375	16	
0.320	0.255	12,840	12,840			6.0	1.36	0.048	3/32	0.372	18	

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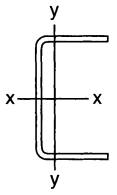
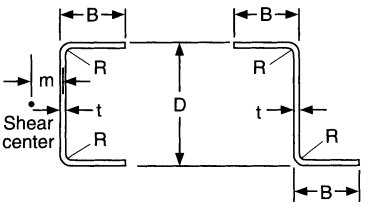
TABLE 9.2 Channel or Zee with Unstiffened Flanges (*Continued*)





Properties of full section (cont'd)		Allowable beam stress f_c		Column factor Q		Dimensions of sections [or]						
Axis *zz*	Product of inertia											
]	]	[or]		[or]								
r min.	I_{xy}					*D*	*B*	*t*	*R*	*m*	Gauge	Size *D* × *B*
in	in	f_b = 20,000 psi	f_b = 30,000 psi	f_b = 20,000 psi	f_b = 30,000 psi	in	in	in	in	in	No.	in
0.287	0.363	20,000	30,000	0.934	0.874	5.0	1.24	0.105	3/16	0.327	12	5 × 1¼
0.267	0.229	18,550	26,490			5.0	1.15	0.075	3/32	0.303	14	
0.263	0.180	17,050	22,870			5.0	1.13	0.060	3/32	0.301	16	
0.243	0.125	15,810	19,850			5.0	1.05	0.048	3/32	0.273	18	
0.274	0.256	20,000	30,000	0.991	0.953	4.0	1.17	0.105	3/16	0.327	12	4 × 1⅛
0.291	0.203	18,180	25,580	0.827	0.734	4.0	1.21	0.075	3/32	0.357	14	
0.271	0.143	17,050	22,870			4.0	1.13	0.060	3/32	0.330	16	
0.267	0.112	15,220	18,430			4.0	1.11	0.048	3/32	0.326	18	
0.276	0.191	20,000	30,000	1.000	1.000	3.0	1.17	0.105	3/16	0.362	12	3 × 1⅛
0.294	0.151	18,180	25,580	0.897	0.815	3.0	1.21	0.075	3/32	0.394	14	

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0.275	0.107	17,050	22,870	0.808	0.694	3.0	1.13	0.060	3/32	0.365	16	
0.272	0.0836	15,220	18,430	0.687	0.538	3.0	1.11	0.048	3/32	0.361	18	
0.262	0.124	20,000	30,000	1.000	1.000	2.0	1.17	0.105	3/16	0.405	12	$2 \times 1\frac{1}{8}$
0.280	0.0993	18,180	25,580	0.909	0.853	2.0	1.21	0.075	3/32	0.439	14	
0.266	0.0705	17,050	22,870	0.853	0.762	2.0	1.13	0.060	3/32	0.408	16	
0.264	0.0553	15,220	18,430	0.759	0.608	2.0	1.11	0.048	3/32	0.404	18	

DIMENSIONS: Equipment and forming practices vary with different manufacturers, resulting in minor variations in some of these dimensions. These minor variations do not affect the published properties. Consult the manufacturer for actual weight per foot and actual dimensions. Column form factors Q for members having webs with w/t ratios in excess of 60 are not shown. See limitations of Section 2.3.3(a) of the Specification applicable to element stiffened by simple lip.

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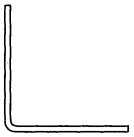
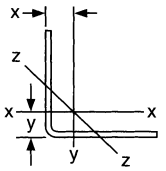
TABLE 9.3 Equal Leg Angle with Unstiffened Legs





Nominal				Properties of full section							Beam strength f_b = 20,000 psi		
					Axis *xx* and Axis *yy*				Axis *zz*		*M* max.		*M* max.
Size	Gauge	*t*	Wt./ft	Area	*I*	*S*	*r*	*x* = *y*	*I*	*r*	f_c	Comp. x–x tension	Comp. x–x tension
in	No.	in	lb	in^2	in^4	in^3	in	in	in^4	in	psi	in • lb	in • lb
4 × 4	10	0.135	3.66	1.05	1.715	0.582	1.28	1.07	0.662	0.794	12,300	7,160	11,640
3 × 3	10	0.135	2.72	0.781	0.712	0.324	0.955	0.819	0.271	0.589	15,340	4,970	6,480
	12	0.105	2.16	0.620	0.586	0.262	0.972	0.817	0.224	0.601	12,600	3,300	5,240
2½ × 2½	10	0.135	2.25	0.646	0.407	0.223	0.793	0.694	0.153	0.487	17,080	3,810	4,460
	12	0.105	1.79	0.515	0.338	0.182	0.811	0.692	0.128	0.499	14,600	2,660	3,640
2 × 2	10	0.135	1.78	0.511	0.204	0.141	0.632	0.569	0.0756	0.385	18,830	2,650	2,820
	12	0.105	1.43	0.410	0.173	0.116	0.649	0.567	0.0643	0.396	16,830	1,950	2,320
	14	0.075	1.08	0.311	0.144	0.092	0.680	0.570	0.0555	0.423	12,590	1,160	1,840
	16	0.060	0.840	0.241	0.104	0.069	0.658	0.545	0.0404	0.409	11,040	760	1,380

NOTE: The allowable bending moments shown in this table apply only when the sections are adequately braced laterally. Where the vertical legs of the angles are in compression, *M* max is based on the values of f_c (see 3.2 of Design Specification) indicated: where the vertical legs of the angles are in tension, *M* max is based on f_b (tension) since the compression stress is always less than f_c for the sections listed. Because it is virtually impossible to load single angle struts concentrically, the design of any such strut should take the eccentricity into account.

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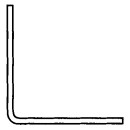
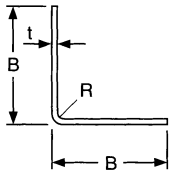
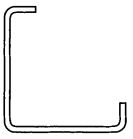


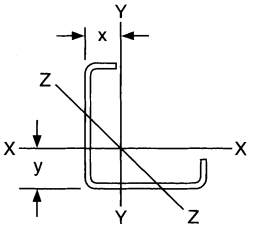


Beam strength (cont'd) f_b = 30,000 psi			Column factor Q		Dimensions of sections					
	M max.	M max.								
f_c	Comp. x–x tension	Comp. x–x tension	f_b = 20,000 psi	f_b = 30,000 psi	B	t	R	Wt./ft	Gauge	Size
psi	in • lb	in • lb			in	in	in	lb	No.	in
12300	7160	17460	0.542	0.361	4.01	0.135	3/16	3.66	10	4 × 4
18730	6070	9720	0.767	0.624	3.01	0.135	3/16	2.72	10	3 × 3
12600	3300	7860	0.587	0.391	3.05	0.105	3/16	2.16	12	
22950	5120	6690	0.854	0.764	2.51	0.135	3/16	2.25	10	2½ × 2½
16920	3080	5460	0.730	0.563	2.55	0.105	3/16	1.79	12	
27150	3830	4230	0.941	0.904	2.01	0.135	3/16	1.78	10	2 × 2
22330	2590	3480	0.842	0.745	2.05	0.105	3/16	1.43	12	
12590	1160	2760	0.586	0.390	2.14	0.075	3/32	1.08	14	
11040	760	2070	0.401	0.267	2.06	0.060	3/32	0.840	16	

DIMENSIONS: Equipment and forming practices vary with different manufacturers, resulting in minor variations in some of these dimensions. These minor variations do not affect the published properties. Consult the manufacturer for actual weight per foot and actual dimensions.

TABLE 9.4 Equal Leg Angle with Stiffened Legs





Nominal				Properties of full section						
					Axis xx and Axis yy				Axis zz	
Size	Gauge	t	Wt./ft	Area	I	S	r	$x = y$	I	r
in	No.	in	lb	in^2	in^4	in^3	in	in	in^4	in
4 × 4	10	0.135	4.46	1.28	2.62	0.962	1.43	1.29	1.25	0.988
3 × 3	10	0.135	3.34	0.957	1.08	0.536	1.06	0.993	0.531	0.745
	12	0.105	2.59	0.743	0.864	0.416	1.08	0.973	0.407	0.740
2½ × 2½	10	0.135	2.68	0.768	0.579	0.342	0.868	0.818	0.277	0.600
	12	0.105	2.15	0.617	0.494	0.286	0.895	0.824	0.236	0.618
2 × 2	10	0.135	2.21	0.633	0.306	0.233	0.695	0.695	0.159	0.501
	12	0.105	1.78	0.512	0.267	0.198	0.722	0.701	0.137	0.517
	14	0.075	1.33	0.381	0.222	0.154	0.763	0.693	0.107	0.530
	16	0.060	1.00	0.287	0.153	0.108	0.731	0.646	0.071	0.497

NOTE: The properties listed in this table apply only when the sections are adequately braced laterally. Unless lipped angle compression struts are checked for torsional buckling, these Q values apply only to situations where such torsional buckling is prevented, as for instance when two angles are connected back to back. Because it is virtually impossible to load single angle struts concentrically, the design of any such strut should take the eccentricity into account.

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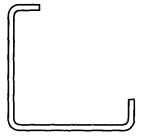

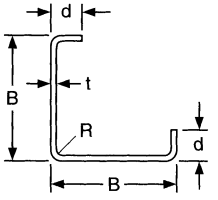

Column form factor		Dimensions of sections						
Q		B	d	t	R	Wt./ft	Gauge	Size
f_b = 20,000 psi	f_b = 30,000 psi	in	in	in	in	lb	No.	in
1.000	0.997	4.01	1.1	0.135	3/16	4.46	10	4 × 4
1.000	1.000	3.01	0.9	0.135	3/16	3.34	10	3 × 3
1.000	1.000	3.05	0.8	0.105	3/16	2.59	12	
1.000	1.000	2.51	0.7	0.135	3/16	2.68	10	2½ × 2½
1.000	1.000	2.55	0.7	0.105	3/16	2.15	12	
1.000	1.000	2.01	0.7	0.135	3/16	2.21	10	2 × 2
1.000	1.000	2.05	0.7	0.105	3/16	1.78	12	
1.000	1.000	2.14	0.6	0.075	3/32	1.33	14	
1.000	0.985	2.06	0.5	0.060	3/32	1.00	16	

DIMENSIONS: Equipment and forming practices vary with different manufacturers, resulting in minor variations in some of these dimensions. These minor variations do not affect the published properties. Consult the manufacturer for actual weight per foot and actual dimensions.

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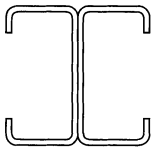
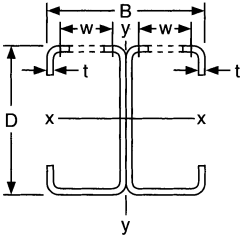
TABLE 9.5 Two Channels with Stiffened Flanges Back to Back



Effective section for beam strength about the *xx* axis where *w/t* of compression flange exceeds 28.4 for f_b = 20,000 psi and 23.2 for f_b = 30,000 psi



Nominal				Beam strength						
				Effective			Properties of full section			
				S_x		S_y		Axis *xx*		
Size $D \times B$	Gauge	t	Wt./ft	f_b = 20,000 psi	f_b = 30,000 psi	f_b = 20,000 f_b = 30,000	Area	I_x	S_x	r_x
in	No.	in	lb	in^3	in^3	in^3	in^2	in^4	in^3	in
12 × 7	10	0.135	18.8	18.7	18.7	3.58	5.40	112.0	18.7	4.56
	12	0.105	14.6	14.6	14.5	2.70	4.20	87.7	14.6	4.57
10 × 7	10	0.135	17.0	14.6	14.6	3.58	4.86	73.0	14.6	3.87
	12	0.105	13.1	11.4	11.3	2.70	3.78	57.0	11.4	3.89
	14	0.075	9.34	7.80	7.44	1.81	2.68	41.0	8.20	3.91
9 × 6½	10	0.135	15.5	12.1	12.1	3.17	4.46	54.3	12.1	3.49
	12	0.105	11.9	9.32	9.30	2.26	3.42	41.9	9.32	3.50
	14	0.075	8.56	6.56	6.30	1.60	2.46	30.6	6.80	3.53
	16	0.060	6.80	4.95	4.72	1.22	1.95	24.3	5.40	3.53
8 × 6	10	0.135	13.9	9.66	9.66	2.63	4.00	38.6	9.66	3.11
	12	0.105	10.8	7.56	7.56	1.98	3.10	30.2	7.56	3.12

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	14	0.075	7.78	5.42	5.24	1.40	2.24	22.1	5.52	3.15
	16	0.060	6.16	4.11	3.91	1.06	1.77	17.6	4.40	3.15
7 × 5½	10	0.135	12.3	7.50	7.50	2.14	3.54	26.2	7.50	2.72
	12	0.105	9.72	5.96	5.96	1.71	2.78	20.9	5.96	2.74
	14	0.075	7.00	4.35	4.22	1.21	2.00	15.3	4.38	2.76
	16	0.060	5.54	3.33	3.18	0.919	1.59	12.2	3.48	2.77
6 × 5	10	0.135	10.7	5.62	5.62	1.71	3.08	16.8	5.62	2.34
	12	0.105	8.46	4.48	4.48	1.37	2.42	13.4	4.48	2.35
	14	0.075	6.20	3.35	3.30	1.04	1.78	10.1	3.36	2.38
	16	0.060	4.92	2.61	2.51	0.785	1.41	8.02	2.68	2.39
5 × 4	10	0.135	8.86	3.76	3.76	1.18	2.54	9.38	3.76	1.92
	12	0.105	7.00	3.02	3.02	0.950	2.00	7.53	3.02	1.94
	14	0.075	5.06	2.24	2.24	0.671	1.45	5.60	2.24	1.96
	16	0.060	4.00	1.78	1.76	0.500	1.15	4.45	1.78	1.97
	18	0.048	3.22	1.41	1.36	0.406	0.922	3.61	1.44	1.98
4 × 4	10	0.135	7.92	2.76	2.76	1.18	2.28	5.51	2.76	1.56
	12	0.105	6.28	2.22	2.22	0.950	1.80	4.44	2.22	1.57
	14	0.075	4.54	1.66	1.66	0.670	1.30	3.33	1.66	1.60
	16	0.060	3.58	1.33	1.31	0.500	1.03	2.66	1.33	1.61
	18	0.048	2.88	1.06	1.02	0.406	0.826	2.16	1.08	1.62
3½ × 4	10	0.135	7.46	2.30	2.30	1.18	2.14	4.01	2.30	1.37
	12	0.105	5.90	1.85	1.85	0.950	1.69	3.24	1.85	1.38
	14	0.075	4.28	1.40	1.40	0.670	1.23	2.45	1.40	1.41
	16	0.060	3.36	1.12	1.10	0.500	0.966	1.96	1.12	1.42
	18	0.048	2.72	0.888	0.852	0.406	0.778	1.59	0.910	1.43
3 × 3½	12	0.105	5.18	1.36	1.36	0.767	1.48	2.04	1.36	1.17
	14	0.075	3.64	1.02	1.02	0.491	1.05	1.53	1.02	1.21
	16	0.060	2.94	0.832	0.832	0.402	0.846	1.25	0.832	1.22
	18	0.048	2.32	0.661	0.644	0.294	0.662	0.995	0.664	1.23

NOTE: The properties of this table apply only when the channels are adequately joined together. See Section 4 of Design Specification.

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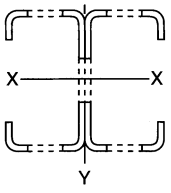
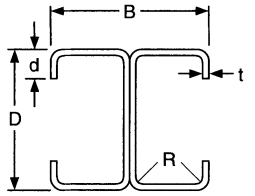
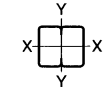
TABLE 9.5 Two Channels with Stiffened Flanges Back to Back (*Continued*)





Properties of full section (cont'd)			Column factor		Dimensions of sections							Nominal	
Axis *yy*			*Q*										
I_y	S_y	r_y	$f_b = 20{,}000$ psi	$f_b = 30{,}000$ psi	D	B	d	t	R	I_y	r_y	Gauge	Size $D \times B$
in^4	in^3	in			in	in	in	in	in	in^4	in	No.	in
12.52	3.58	1.52	0.751	0.703	12.0	7.0	1.0	0.135	3/16	44.28	2.86	10	12 × 7
9.45	2.70	1.50	0.689	0.640	12.0	7.0	0.9	0.105	3/16	34.95	2.88	12	
12.52	3.58	1.60	0.819	0.770	10.0	7.0	1.0	0.135	3/16	38.00	2.80	10	10 × 7
9.45	2.70	1.58	0.756	0.705	10.0	7.0	0.9	0.105	3/16	29.96	2.81	12	
6.33	1.81	1.54	0.634	0.567	10.0	7.0	0.7	0.075	3/32	21.80	2.85	14	
10.31	3.17	1.52	0.852	0.803	9.0	6.5	1.0	0.135	3/16	29.45	2.57	10	9 × 6½
7.34	2.26	1.47	0.785	0.737	9.0	6.5	0.8	0.105	3/16	23.25	2.60	12	
5.19	1.60	1.45	0.674	0.607	9.0	6.5	0.7	0.075	3/32	16.98	2.62	14	
3.96	1.22	1.42	0.590	0.522	9.0	6.5	0.6	0.060	3/32	13.67	2.65	16	
7.90	2.63	1.41	0.887	0.837	8.0	6.0	0.9	0.135	3/16	22.28	2.36	10	8 × 6
5.94	1.98	1.38	0.821	0.774	8.0	6.0	0.8	0.105	3/16	17.60	2.38	12	
4.20	1.40	1.37	0.719	0.653	8.0	6.0	0.7	0.075	3/32	12.92	2.40	14	
3.19	1.06	1.34	0.635	0.565	8.0	6.0	0.6	0.060	3/32	10.39	2.42	16	

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5.90	2.14	1.29	0.924	0.876	7.0	5.5	0.8	0.135	3/16	16.38	2.15	10	7 × 5½
4.72	1.71	1.30	0.861	0.814	7.0	5.5	0.8	0.105	3/16	12.93	2.16	12	
3.33	1.21	1.29	0.764	0.701	7.0	5.5	0.7	0.075	3/32	9.49	2.18	14	
2.53	0.919	1.26	0.686	0.615	7.0	5.5	0.6	0.060	3/32	7.68	2.20	16	
4.26	1.71	1.18	0.962	0.919	6.0	5.0	0.7	0.135	3/16	11.60	1.94	10	6 × 5
3.42	1.37	1.19	0.905	0.858	6.0	5.0	0.7	0.105	3/16	9.18	1.95	12	
2.60	1.04	1.21	0.815	0.759	6.0	5.0	0.7	0.075	3/32	6.78	1.95	14	
1.96	0.785	1.18	0.744	0.674	6.0	5.0	0.6	0.060	3/32	5.48	1.97	16	
2.36	1.18	0.962	0.994	0.964	5.0	4.0	0.7	0.135	3/16	5.97	1.53	10	5 × 4
1.90	0.950	0.973	0.951	0.907	5.0	4.0	0.7	0.105	3/16	4.75	1.54	12	
1.34	0.671	0.961	0.858	0.811	5.0	4.0	0.6	0.075	3/32	3.54	1.56	14	
1.00	0.500	0.934	0.801	0.745	5.0	4.0	0.5	0.060	3/32	2.86	1.58	16	
0.813	0.406	0.939	0.737	0.670	5.0	4.0	0.5	0.048	3/32	2.31	1.58	18	
2.35	1.18	1.02	1.000	0.998	4.0	4.0	0.7	0.135	3/16	4.98	1.48	10	4 × 4
1.90	0.950	1.03	0.994	0.968	4.0	4.0	0.7	0.105	3/16	3.97	1.49	12	
1.34	0.670	1.02	0.926	0.885	4.0	4.0	0.6	0.075	3/32	2.96	1.51	14	
1.00	0.500	0.987	0.875	0.821	4.0	4.0	0.5	0.060	3/32	2.40	1.53	16	
0.812	0.406	0.992	0.810	0.738	4.0	4.0	0.5	0.048	3/32	1.94	1.53	18	
2.35	1.18	1.05	1.000	1.000	3.5	4.0	0.7	0.135	3/16	4.47	1.45	10	3½ × 4
1.90	0.950	1.06	1.000	0.991	3.5	4.0	0.7	0.105	3/16	3.57	1.45	12	
1.34	0.670	1.05	0.959	0.922	3.5	4.0	0.6	0.075	3/32	2.67	1.48	14	
1.00	0.500	1.02	0.914	0.861	3.5	4.0	0.5	0.060	3/32	2.16	1.50	16	
0.812	0.406	1.02	0.851	0.779	3.5	4.0	0.5	0.048	3/32	1.75	1.50	18	
1.34	0.767	0.951	1.000	1.000	3.0	3.5	0.7	0.105	3/16	2.31	1.25	12	3 × 3½
0.860	0.491	0.906	0.985	0.954	3.0	3.5	0.5	0.075	3/32	1.74	1.29	14	
0.703	0.402	0.912	0.949	0.910	3.0	3.5	0.5	0.060	3/32	1.41	1.29	16	
0.515	0.294	0.881	0.900	0.840	3.0	3.5	0.4	0.048	3/32	1.14	1.31	18	

DIMENSIONS: Equipment and forming practices vary with different manufacturers, resulting in minor variations in some of these dimensions. These minor variations do not affect the published properties. Consult the manufacturer for actual weight per foot and actual dimensions.

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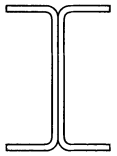
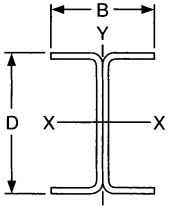
TABLE 9.6 Two Channels with Unstiffened Flanges Back to Back





Nominal				Properties of full section						
					Axis xx			Axis yy		
Size $D \times B$	Gauge	t	Wt./ft	Area	I_x	S_x	r_x	I_y	S_y	r_y
in	No.	in	lb	in^2	in^4	in^3	in	in^4	in^3	in
8×4	10	0.135	10.8	3.10	25.8	6.48	2.89	1.38	0.704	0.669
	12	0.105	8.46	2.42	20.6	5.14	2.91	1.10	0.555	0.674
	14	0.075	6.16	1.77	15.3	3.82	2.94	0.834	0.411	0.687
	16	0.060	4.88	1.40	12.0	3.00	2.93	0.586	0.303	0.647
7×3	10	0.135	8.78	2.52	15.1	4.30	2.45	0.510	0.363	0.450
	12	0.105	7.00	2.00	12.4	3.54	2.48	0.464	0.313	0.481
	14	0.075	5.06	1.45	9.08	2.60	2.50	0.315	0.215	0.466
	16	0.060	3.98	1.14	7.08	2.02	2.49	0.211	0.152	0.429
6×3	10	0.135	7.82	2.24	10.2	3.40	2.13	0.509	0.362	0.476
	12	0.105	6.26	1.80	8.44	2.80	2.17	0.464	0.312	0.508
	14	0.075	4.52	1.30	6.20	2.06	2.19	0.315	0.215	0.492
	16	0.060	3.56	1.02	4.84	1.61	2.17	0.211	0.152	0.454
	18	0.048	2.86	0.818	3.88	1.29	2.18	0.162	0.119	0.445

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5 × 2½	12	0.105	5.16	1.48	4.76	1.91	1.79	0.268	0.217	0.425
	14	0.075	3.68	1.06	3.42	1.37	1.80	0.154	0.134	0.382
	16	0.060	2.94	0.844	2.74	1.09	1.80	0.116	0.103	0.370
	18	0.048	2.30	0.662	2.12	0.846	1.79	0.074	0.071	0.335
4 × 2¼	12	0.105	4.34	1.25	2.66	1.33	1.46	0.229	0.195	0.429
	14	0.075	3.22	0.924	2.04	1.02	1.49	0.180	0.148	0.441
	16	0.060	2.52	0.724	1.58	0.792	1.48	0.116	0.103	0.400
	18	0.048	2.02	0.578	1.27	0.636	1.48	0.088	0.079	0.390
3 × 2¼	12	0.105	3.60	1.04	1.32	0.878	1.13	0.228	0.195	0.470
	14	0.075	2.70	0.774	1.03	0.688	1.15	0.180	0.148	0.481
	16	0.060	2.10	0.604	0.796	0.530	1.15	0.115	0.102	0.437
	18	0.048	1.68	0.482	0.638	0.426	1.15	0.088	0.079	0.427
2 × 2¼	12	0.105	2.88	0.826	0.500	0.500	0.779	0.227	0.194	0.525
	14	0.075	2.18	0.624	0.400	0.400	0.800	0.179	0.148	0.536
	16	0.060	1.69	0.484	0.308	0.308	0.799	0.115	0.102	0.488
	18	0.048	1.35	0.386	0.248	0.248	0.802	0.088	0.079	0.477

NOTE: The properties of this table apply only when the channels are adequately joined together. See Section 4 of Design Specification.

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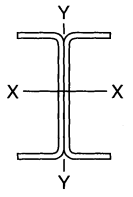
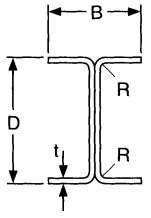
TABLE 9.6 Two Channels with Unstiffened Flanges Back to Back (*Continued*)





Allowable beam stress f_c, psi		Column factor Q		Dimensions of sections						
$f_b = 20{,}000$ psi	$f_b = 30{,}000$ psi	$f_b = 20{,}000$ psi	$f_b = 30{,}000$ psi	D in	B in	t in	R in	Wt./ft lb	Gauge No.	Size $D \times B$ in
18960	27490	0.817	0.736	8.0	3.934	0.135	3/16	10.8	10	8 × 4
17100	22980			8.0	3.972	0.105	3/16	8.46	12	
13040	13150			8.0	4.052	0.075	3/32	6.16	14	
11610	11610			8.0	3.882	0.060	3/32	4.88	16	
20000	30000	0.893	0.825	7.0	2.810	0.135	3/16	8.78	10	7 × 3
19340	28400			7.0	2.972	0.105	3/16	7.00	12	
16610	21790			7.0	2.928	0.075	3/32	5.06	14	
15090	18130			7.0	2.758	0.060	3/32	3.98	16	
20000	30000	0.948	0.889	6.0	2.810	0.135	3/16	7.82	10	6 × 3
19340	28400	0.849	0.774	6.0	2.972	0.105	3/16	6.26	12	
16610	21790			6.0	2.928	0.075	3/32	4.52	14	
15090	18130			6.0	2.758	0.060	3/32	3.56	16	
12840	12840			6.0	2.722	0.048	3/32	2.86	18	

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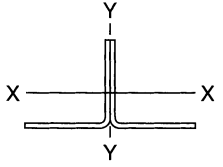
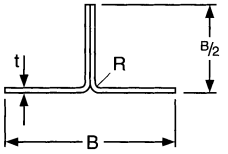
20000	30000	0.934	0.874	5.0	2.472	0.105	3/16	5.16	12	5 × 2½
18550	26490			5.0	2.302	0.075	3/32	3.68	14	
17050	22870			5.0	2.258	0.060	3/32	2.94	16	
15810	19850			5.0	2.098	0.048	3/32	2.30	18	
20000	30000	0.991	0.953	4.0	2.346	0.105	3/16	4.34	12	4 × 2¼
18180	25580	0.827	0.734	4.0	2.428	0.075	3/32	3.22	14	
17050	22870			4.0	2.258	0.060	3/32	2.52	16	
15220	18430			4.0	2.222	0.048	3/32	2.02	18	
20000	30000	1.000	1.000	3.0	2.346	0.105	3/16	3.60	12	3 × 2¼
18180	25580	0.897	0.815	3.0	2.428	0.075	3/32	2.70	14	
17050	22870	0.808	0.694	3.0	2.258	0.060	3/32	2.10	16	
15220	18430	0.687	0.538	3.0	2.222	0.048	3/32	1.68	18	
20000	30000	1.000	1.000	2.0	2.346	0.105	3/16	2.88	12	2 × 2¼
18180	25580	0.909	0.853	2.0	2.428	0.075	3/32	2.18	14	
17050	22870	0.853	0.762	2.0	2.258	0.060	3/32	1.69	16	
15220	18430	0.759	0.608	2.0	2.222	0.048	3/32	1.35	18	

DIMENSIONS: Equipment and forming practices vary with different manufacturers, resulting in minor variations in some of these dimensions. These minor variations do not affect the published properties. Consult the manufacturer for actual weight per foot and actual dimensions. Column form factors Q for members having webs with w/t-ratios in excess of 60 are not shown. See limitations of Section 2.3.3(a) of the Specification applicable to element stiffened by simple lip.

TABLE 9.7 Two Equal-Leg Angles, Back to Back, Unstiffened Legs





Column properties					Dimensions				
Full theoretical outline			Q						
Area	r_x	r_y	$f_b = 20{,}000$	$f_b = 30{,}000$	B	Thickness t	Radius R	Weight per ft	Nominal size
in^2	in	in	psi	psi	in	in	in	lb	in
2.10	1.28	1.67	0.542	0.361	8.030	.135	3/16	7.32	4 × 4
1.56	0.955	1.26	0.767	0.624	6.030	.135	3/16	5.44	3 × 3
1.24	0.972	1.27	0.587	0.391	6.110	.105	3/16	4.32	
1.29	0.793	1.05	0.854	0.764	5.030	.135	3/16	4.50	2½ × 2½
1.03	0.811	1.07	0.730	0.563	5.110	.105	3/16	3.58	
1.02	0.632	0.850	0.941	0.904	4.030	.135	3/16	3.56	2 × 2
0.820	0.649	0.862	0.842	0.745	4.110	.105	3/16	2.86	
0.622	0.680	0.887	0.586	0.390	4.276	.075	3/32	2.16	
0.482	0.658	0.855	0.401	0.267	4.128	.060	3/32	1.68	

DIMENSIONS: Equipment and forming practices vary with different manufacturers, resulting in minor variations in some of these dimensions. These minor variations do not affect the published properties. Consult the manufacturer for actual weight per foot and actual dimensions.

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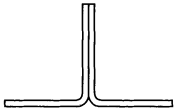

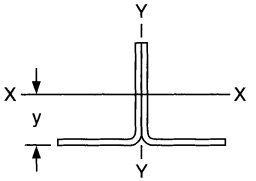

Nominal (one angle)			Section modulus based on full theoretical outline	Beam strength						Deflection	
				f_b = 20,000 psi			f_b = 30,000 psi			Any grade of steel	
				M max.			M max.				
Size	Gauge	Thickness	S_z	f_c	Comp. x-x tension	Comp. x-x tension	f_c	Comp. x-x tension	Comp. x-x tension	y	I_x
in	No.	in	in^3	psi	in • lb	in • lb	psi	in • lb	in • lb	in	in^4
4 × 4	10	.135	1.164	12300	14320	23280	12300	14320	34920	1.069	3.430
3 × 3	10	.135	0.648	15340	9940	12960	18730	12140	19440	0.819	1.424
	12	.105	0.524	12600	6600	10480	12600	6600	15720	0.817	1.172
2½ × 2½	10	.135	0.446	17090	7620	8920	22950	10230	13380	0.694	0.814
	12	.105	0.364	14600	5310	7280	16920	6160	10920	0.692	0.676
2 × 2	10	.135	0.282	18830	5310	5640	27150	7660	8460	0.569	0.408
	12	.105	0.232	16830	3910	4640	22330	5180	6960	0.567	0.346
	14	.075	0.183	12590	2320	3680	12590	2320	5520	0.570	0.288
	16	.060	0.137	11040	1520	2760	11040	1520	4140	0.546	0.208

NOTE: The properties of this table may be used only when the angles are adequately joined and adequately braced laterally. Q is the column factor (Sec. 3.6.1, Design Specification). Where the vertical legs of the angles are in compression M_{max} is based on the values of f_c (Sec. 3.2 of Design Specification) indicated; where the vertical legs of the angles are in tension M_{max} is based on f_b (tension) since the compression stress is always less than f_c for the sections listed.

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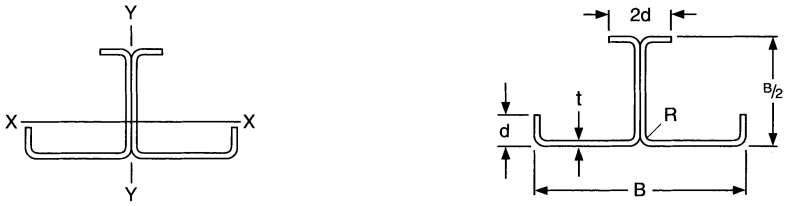
TABLE 9.8 Two Equal-Leg Angles, Back to Back, Stiffened Legs



Column form factor		Dimensions of sections						
Q		B	d	t	R	Wt./ft	Gauge	Size
f_b = 20,000 psi	f_b = 30,000 psi	in	in	in	in	lb	No.	in
1.000	0.997	8.030	1.1	0.135	3/16	8.92	10	4 × 4
1.000	1.000	6.030	0.9	0.135	3/16	6.68	10	3 × 3
1.000	1.000	6.110	0.8	0.105	3/16	5.18	12	
1.000	1.000	5.030	0.7	0.135	3/16	5.36	10	2½ × 2½
1.000	1.000	5.110	0.7	0.105	3/16	4.30	12	
1.000	1.000	4.030	0.7	0.135	3/16	4.42	10	2 × 2
1.000	1.000	4.110	0.7	0.105	3/16	3.56	12	
1.000	1.000	4.276	0.6	0.075	3/32	2.66	14	
1.000	0.985	4.128	0.5	0.060	3/32	2.00	16	

DIMENSIONS: Equipment and forming practices vary with different manufacturers, resulting in minor variations in some of these dimensions. These minor variations do not affect the published properties. Consult the manufacturer for actual weight per foot and actual dimensions.

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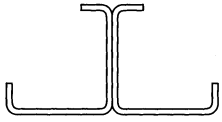

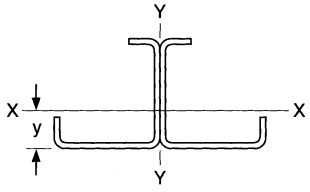

Nominal (one angle)			Wt./ft	Properties of full section						
				Area	Axis *xx*				Axis *yy*	
Size	Gauge	Thickness			*I*	*S*	*r*	*y*	*I*	*r*
in	No.	in	lb	in^2	in^4	in^3	in	in	in^4	in
4 × 4	10	0.135	8.92	2.56	5.23	1.92	1.43	1.29	9.51	1.93
3 × 3	10	0.135	6.68	1.91	2.16	1.07	1.06	0.993	4.05	1.46
	12	0.105	5.18	1.49	1.73	0.832	1.08	0.973	3.13	1.45
2½ × 2½	10	0.135	5.36	1.54	1.16	0.684	0.868	0.818	2.19	1.19
	12	0.105	4.30	1.23	0.989	0.572	0.895	0.824	1.83	1.22
2 × 2	10	0.135	4.42	1.27	0.612	0.466	0.695	0.695	1.22	0.981
	12	0.105	3.56	1.02	0.534	0.396	0.722	0.701	1.04	1.008
	14	0.075	2.66	0.762	0.444	0.308	0.763	0.693	0.810	1.031
	16	0.060	2.00	0.574	0.306	0.216	0.731	0.646	0.546	0.975

NOTE: The properties listed in this table may be used only when the angles are adequately joined and adequately braced laterally.

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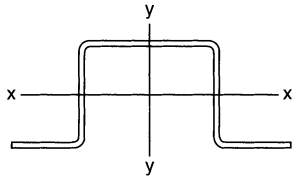
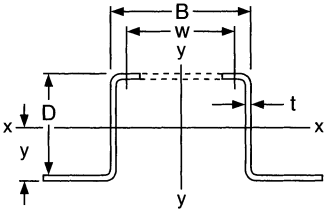
TABLE 9.9 Hat Sections



Effective section for beam strength about the *xx* axis where w/t of compression flange exceeds 28.4 for f_b = 20,000 psi and 23.2 for f_b = 30,000 psi



Nominal Size $D \times B$	Gauge	t	Wt./ft	For beam strength calculations: Comp. x–x tension, f_b = 20,000 psi, S_x	For beam strength calculations: Comp. x–x tension, f_b = 20,000 psi, S'_x	For beam strength calculations: Comp. x–x tension, f_b = 30,000 psi, S_x	For beam strength calculations: Comp. x–x tension, f_b = 30,000 psi, S'_x	For deflection calculations: Comp. x–x tension, Full section, I_x	For deflection calculations: Comp. x–x tension, f_b = 20,000 psi, I_x	For deflection calculations: Comp. x–x tension, f_b = 30,000 psi, I_x	For deflection calculations: Comp. x–x tension, I'_x	For column strength: Full (solid) section, Area	For column strength: Full (solid) section, r_x	For column strength: Full (solid) section, r_y
in	No.	in	lb	in^3	in^3	in^3	in^3	in^4	in^4	in^4	in^4	in^2	in	in
10 × 15	10	0.135	17.15	9.45	10.3	9.18	10.3	67.5	59.1	55.5	67.5	5.04	3.66	6.46
	12	0.105	13.2	6.66	7.54	6.46	7.54	50.2	41.0	38.4	50.2	3.87	3.60	6.42
10 × 10	12	0.105	11.4	6.57	7.11	6.40	7.11	43.6	39.4	37.3	43.6	3.34	3.61	4.47
	14	0.075	7.98	4.12	4.68	4.00	4.68	29.4	24.3	23.0	29.4	2.35	3.54	4.44
10 × 5	14	0.075	6.71	4.02	4.19	3.93	4.19	23.4	22.6	21.8	23.4	1.97	3.45	2.34
8 × 12	10	0.135	13.9	6.68	7.09	6.51	7.09	36.3	33.6	31.8	36.3	4.10	2.98	5.21
	12	0.105	10.7	4.68	5.13	4.55	5.13	26.8	23.3	21.9	26.8	3.13	2.93	5.17
8 × 8	12	0.105	9.23	4.60	4.83	4.49	4.83	23.3	22.1	21.1	23.3	2.71	2.93	3.60
	14	0.075	6.45	2.85	3.14	2.77	3.14	15.6	13.6	12.9	15.6	1.90	2.87	3.56
8 × 4	14	0.075	5.43	2.76	2.81	2.71	2.81	12.4	12.3	12.0	12.4	1.60	2.78	1.88
	16	0.060	4.29	2.06	2.15	2.02	2.15	9.61	9.28	8.97	9.61	1.26	2.76	1.87
6 × 9	10	0.135	10.7	4.31	4.43	4.21	4.43	16.4	16.0	15.4	16.4	3.15	2.28	3.97
	12	0.105	8.16	3.00	3.16	2.92	3.16	12.1	11.3	10.7	12.1	2.40	2.24	3.92

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6 × 6	12	0.105	7.09	2.92	2.98	2.87	2.98	10.4	10.3	10.0	10.4	2.08	2.24	2.74
	14	0.075	4.92	1.79	1.90	1.75	1.90	6.91	6.47	6.16	6.91	1.45	2.18	2.69
6 × 3	14	0.075	4.16	1.70	1.70	1.68	1.70	5.48	5.44	5.46	5.48	1.22	2.12	1.43
	16	0.060	3.27	1.27	1.29	1.25	1.29	4.23	4.21	4.13	4.23	0.963	2.10	1.42
	18	0.048	2.59	0.954	0.986	0.93	0.984	3.28	3.20	3.10	3.28	0.761	2.08	1.41
4 × 6	10	0.135	7.51	2.34	2.35	2.31	2.35	5.43	5.43	5.40	5.43	2.21	1.57	2.76
	12	0.105	5.66	1.62	1.65	1.59	1.65	3.96	3.94	3.83	3.96	1.66	1.54	2.69
4 × 4	12	0.105	4.94	1.55	1.55	1.54	1.55	3.39	3.39	3.39	3.39	1.45	1.53	1.91
	14	0.075	3.39	0.945	0.961	0.928	0.961	2.23	2.22	2.16	2.23	0.998	1.49	1.83
4 × 2	14	0.075	2.88	0.863	0.863	0.863	0.863	1.75	1.75	1.75	1.75	0.848	1.44	0.996
	16	0.060	2.25	0.639	0.643	0.641	0.643	1.34	1.34	1.34	1.34	0.663	1.42	0.972
	18	0.048	1.77	0.482	0.483	0.477	0.483	1.03	1.03	1.03	1.03	0.520	1.41	0.956
3 × 4½	10	0.135	5.90	1.51	1.51	1.52	1.52	2.47	2.47	2.46	2.47	1.736	1.19	2.19
	12	0.105	4.41	1.05	1.05	1.04	1.05	1.81	1.81	1.80	1.81	1.297	1.18	2.09
3 × 3	12	0.105	3.87	0.993	0.993	0.993	0.993	1.53	1.53	1.53	1.53	1.139	1.16	1.52
	14	0.075	2.63	0.603	0.604	0.597	0.604	1.01	1.01	1.00	1.01	0.773	1.14	1.41
3 × 1½	14	0.075	2.25	0.504	0.504	0.504	0.504	0.784	0.784	0.784	0.784	0.660	1.09	0.793
	16	0.060	1.74	0.400	0.400	0.400	0.400	0.599	0.599	0.599	0.599	0.513	1.08	0.760
	18	0.048	1.36	0.297	0.297	0.297	0.297	0.459	0.459	0.459	0.459	0.400	1.07	0.738
2 × 4	12	0.105	3.52	0.596	0.596	0.593	0.596	0.672	0.672	0.671	0.672	1.03	0.806	1.90
	14	0.075	2.37	0.350	0.353	0.345	0.353	0.433	0.432	0.423	0.433	0.698	0.787	1.77
2 × 2	14	0.075	1.86	0.321	0.321	0.321	0.321	0.329	0.329	0.329	0.329	0.548	0.774	1.01
	16	0.060	1.44	0.233	0.233	0.233	0.233	0.250	0.248	0.248	0.250	0.423	0.768	0.973
2 × 1	16	0.060	1.23	0.178	0.178	0.178	0.178	0.193	0.193	0.193	0.193	0.363	0.729	0.566
	18	0.048	0.953	0.142	0.142	0.142	0.142	0.147	0.147	0.147	0.147	0.280	0.725	0.532
1½ × 3	12	0.105	2.80	0.390	0.390	0.390	0.390	0.304	0.304	0.304	0.304	0.824	0.607	1.54
	14	0.075	1.86	0.230	0.230	0.228	0.230	0.198	0.198	0.198	0.198	0.548	0.602	1.39
1½ × 1½	14	0.075	1.48	0.187	0.187	0.187	0.187	0.148	0.148	0.148	0.148	0.435	0.583	0.832
	16	0.060	1.13	0.150	0.150	0.150	0.150	0.113	0.113	0.113	0.113	0.333	0.582	0.779
1½ × ¾	16	0.060	0.979	0.0993	0.0993	0.0993	0.0993	0.0856	0.0856	0.086	0.0856	0.288	0.545	0.484
	18	0.048	0.749	0.0795	0.0795	0.0795	0.0795	0.0657	0.0657	0.066	0.0657	0.220	0.546	0.442

NOTE: $S'x$ and $I'x$ in this table are properties of full (unreduced) section and are applicable as indicated. The effective section moduli in bending about the yy axis have not been tabulated. When one of the webs acts as a compression flange the section modulus should be calculated on the basis of its effective width as provided in Section 2.3 of the Design Specification. When the web acts as a tension flange the section modulus of the full section is effective.

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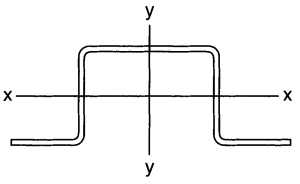
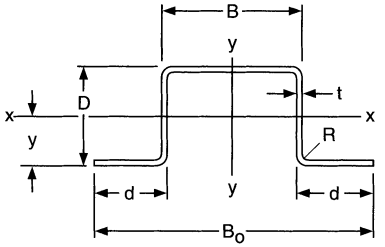
TABLE 9.9 Hat Sections (*Continued*)





Column factor		Additional properties of full (unreduced) sections			Dimensions of sections								
Q		S_y	I_y	y	D	B	B_o	d	t	R	Wt./ft	Gauge	Size $D \times B$
f_b = 20,000 psi	f_b = 30,000 psi	in^3	in^4	in	in	in	in	in	in	in	lb	No.	in
		23.3	210.3	6.54	10.0	15.0	18.07	1.67	0.135	3/16	17.15	10	10 × 15
		18.3	159.5	6.65	10.0	15.0	17.47	1.34	0.105	3/16	13.2	12	
		10.7	66.77	6.14	10.0	10.0	12.47	1.34	0.105	3/16	11.4	12	10 × 10
		7.91	46.21	6.30	10.0	10.0	11.68	0.915	0.075	3/32	7.98	14	
		3.23	10.79	5.60	10.0	5.0	6.68	0.915	0.075	3/32	6.71	14	10 × 5
		14.8	111.2	5.12	8.0	12.0	15.07	1.67	0.135	3/16	13.9	10	8 × 12
		11.6	83.63	5.23	8.0	12.0	14.47	1.34	0.105	3/16	10.7	12	
		6.72	35.21	4.81	8.0	8.0	10.47	1.34	0.105	3/16	9.23	12	8 × 8
		4.97	24.07	4.97	8.0	8.0	9.68	0.915	0.075	3/32	6.45	14	
		1.99	5.66	4.40	8.0	4.0	5.68	0.915	0.075	3/32	5.43	14	8 × 4
		1.65	4.43	4.47	8.0	4.0	5.38	0.75	0.060	3/32	4.29	16	
0.859	0.781	8.24	49.74	3.71	6.0	9.0	12.07	1.67	0.135	3/16	10.7	10	6 × 9
0.751	0.671	6.42	36.84	3.82	6.0	9.0	11.47	1.34	0.105	3/16	8.16	12	
0.835	0.752	3.71	15.70	3.49	6.0	6.0	8.47	1.34	0.105	3/16	7.09	12	6 × 6
		2.73	10.48	3.64	6.0	6.0	7.68	0.915	0.075	3/32	4.92	14	
		1.07	2.51	3.21	6.0	3.0	4.68	0.915	0.075	3/32	4.16	14	6 × 3

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		0.883	1.93	3.28	6.0	3.0	4.38	0.75	0.060	3/32	3.27	16	
		0.728	1.51	3.33	6.0	3.0	4.14	0.618	0.048	3/32	2.59	18	
0.974	0.942	3.72	16.86	2.31	4.0	6.0	9.07	1.67	0.135	3/16	7.51	10	4 × 6
0.924	0.861	2.84	12.05	2.41	4.0	6.0	8.47	1.34	0.105	3/16	5.66	12	
0.988	0.939	1.64	5.31	2.19	4.0	4.0	6.47	1.34	0.105	3/16	4.94	12	4 × 4
0.856	0.773	1.18	3.35	2.32	4.0	4.0	5.68	0.915	0.075	3/32	3.39	14	
0.887	0.822	0.457	0.842	2.03	4.0	2.0	3.68	0.915	0.075	3/32	2.88	14	4 × 2
		0.369	0.626	2.09	4.0	2.0	3.38	0.75	0.060	3/32	2.25	16	
		0.303	0.476	2.14	4.0	2.0	3.14	0.618	0.048	3/32	1.77	18	
1.000	0.990	2.19	8.28	1.63	3.0	4.5	7.57	1.67	0.135	3/16	5.90	10	3 × 4½
0.982	0.955	1.63	5.69	1.71	3.0	4.5	6.97	1.34	0.105	3/16	4.41	12	
1.000	1.000	0.956	2.62	1.54	3.0	3.0	5.47	1.34	0.105	3/16	3.87	12	3 × 3
0.969	0.907	0.659	1.54	1.67	3.0	3.0	4.68	0.915	0.075	3/32	2.63	14	
0.976	0.928	0.261	0.415	1.45	3.0	1.5	3.18	0.915	0.075	3/32	2.25	14	3 × 1½
0.915	0.853	0.205	0.296	1.50	3.0	1.5	2.88	0.75	0.060	3/32	1.74	16	
0.839	0.772	0.165	0.218	1.55	3.0	1.5	2.64	0.618	0.048	3/32	1.36	18	
0.994	0.971	1.15	3.72	1.13	2.0	4.0	6.47	1.34	0.105	3/16	3.52	12	2 × 4
0.931	0.892	0.772	2.19	1.22	2.0	4.0	5.68	0.915	0.075	3/32	2.37	14	
1.000	1.000	0.307	0.564	1.02	2.0	2.0	3.68	0.915	0.075	3/32	1.86	14	2 × 2
1.000	0.978	0.237	0.400	1.07	2.0	2.0	3.38	0.75	0.060	3/32	1.44	16	
1.000	0.982	0.0976	0.116	0.920	2.0	1.0	2.38	0.75	0.060	3/32	1.23	16	2 × 1
0.975	0.928	0.0743	0.0795	0.961	2.0	1.0	2.14	0.618	0.048	3/32	0.953	18	
1.000	1.000	0.715	1.96	0.778	1.5	3.0	5.47	1.34	0.105	3/16	2.80	12	1½ × 3
0.986	0.956	0.454	1.06	0.864	1.5	3.0	4.68	0.915	0.075	3/32	1.86	14	
1.000	1.000	0.189	0.301	0.709	1.5	1.5	3.18	0.915	0.075	3/32	1.48	14	1½ × 1½
1.000	1.000	0.141	0.202	0.750	1.5	1.5	2.88	0.75	0.060	3/32	1.13	16	
1.000	1.000	0.0633	0.0674	0.637	1.5	0.75	2.13	0.75	0.060	3/32	0.979	16	1½ × ¾
1.000	0.996	0.0455	0.0430	0.673	1.5	0.75	1.89	0.618	0.048	3/32	0.749	18	

DIMENSIONS: Equipment and forming practices vary with different manufacturers, resulting in minor variations in some of these dimensions. These minor variations do not affect the published properties. Consult the manufacturer for actual weight per foot and actual dimensions. Column form factors Q for members having webs with w/t-ratios in excess of 60 are not shown. See limitations of Section 2.3.3(a) of the Specification applicable to element stiffened by a simple lip.

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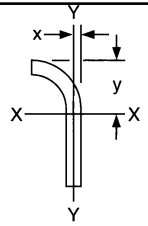
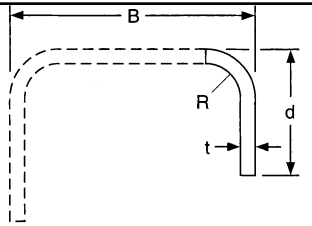
TABLE 9.10 One-Flange Stiffener (Which Includes One 90° Corner): Properties and Dimensions



Stock Width of Blank Taken at $t/3$ Distance From Inner Surface.



Nominal Gauge No.	Thickness t in	Depth d in	Properties: xx Axis I_x in^4	xx Axis y in	yy Axis I_y in^4	yy Axis x in	Area in^2	Dimensions: Max. flange B in	Blank width in	Thickness t in	Radius R in	Depth d in	Nominal Gauge No.
		1.0	0.01255	0.4737	0.000796	0.1005	0.14554	3.87	1.043	0.135	3/16	1.0	
		0.9	0.00916	0.4250	0.000759	0.1039	0.13204	3.25	0.943	0.135	3/16	0.9	
		0.8	0.00643	0.3766	0.000719	0.1080	0.11854	2.81	0.843	0.135	3/16	0.8	
10	0.135	0.7	0.00430	0.3286	0.000674	0.1133	0.10504	2.53	0.743	0.135	3/16	0.7	10
		0.6	0.00269	0.2811	0.000621	0.1200	0.09154	2.37	0.643	0.135	3/16	0.6	
		0.5	0.00153	0.2346	0.000556	0.1291	0.07804	2.30	0.543	0.135	3/16	0.5	
		0.4	0.00076	0.1896	0.000474	0.1420	0.06454	2.27	0.443	0.135	3/16	0.4	
		0.9	0.00735	0.4205	0.000475	0.0850	0.10337	4.28	0.957	0.105	3/16	0.9	
		0.8	0.00518	0.3719	0.000453	0.0886	0.09287	3.34	0.857	0.105	3/16	0.8	
		0.7	0.00348	0.3237	0.000428	0.0932	0.08237	2.66	0.757	0.105	3/16	0.7	
12	0.105	0.6	0.00219	0.2761	0.000398	0.0992	0.07187	2.22	0.657	0.105	3/16	0.6	12
		0.5	0.00126	0.2292	0.000362	0.1072	0.06137	1.98	0.557	0.105	3/16	0.5	
		0.4	0.00064	0.1836	0.000314	0.1185	0.05087	1.88	0.457	0.105	3/16	0.4	

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		0.9	0.00493	0.4351	0.000081	0.0475	0.07031	6.79	0.918	0.075	3/32	0.9	
		0.8	0.00348	0.3855	0.000076	0.0487	0.06281	4.94	0.818	0.075	3/32	0.8	
14	0.075	0.7	0.00234	0.3361	0.000072	0.0502	0.05531	3.50	0.718	0.075	3/32	0.7	14
		0.6	0.00148	0.2869	0.000067	0.0522	0.04781	2.46	0.618	0.075	3/32	0.6	
		0.5	0.00086	0.2379	0.000062	0.0549	0.04031	1.77	0.518	0.075	3/32	0.5	
		0.4	0.00044	0.1894	0.000055	0.0589	0.03281	1.40	0.418	0.075	3/32	0.4	
		0.8	0.00283	0.3836	0.000048	0.0400	0.05044	7.50	0.825	0.060	3/32	0.8	
		0.7	0.00191	0.3341	0.000045	0.0414	0.04444	5.19	0.725	0.060	3/32	0.7	
16	0.060	0.6	0.00121	0.2848	0.000043	0.0432	0.03844	3.46	0.625	0.060	3/32	0.6	16
		0.5	0.00071	0.2357	0.000040	0.0456	0.03244	2.23	0.525	0.060	3/32	0.5	
		0.4	0.00036	0.1871	0.000036	0.0492	0.02644	1.48	0.425	0.060	3/32	0.4	
		0.7	0.00155	0.3325	0.000030	0.0344	0.03567	7.96	0.731	0.048	3/32	0.7	
		0.6	0.00099	0.2831	0.000028	0.0360	0.03087	5.19	0.631	0.048	3/32	0.6	
18	0.048	0.5	0.00058	0.2340	0.000026	0.0382	0.02607	3.20	0.531	0.048	3/32	0.5	18
		0.4	0.00030	0.1853	0.000024	0.0414	0.02127	1.87	0.431	0.048	3/32	0.4	

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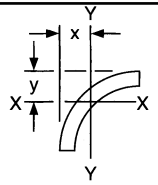
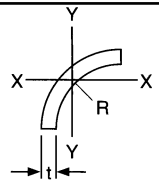
TABLE 9.11 One 90° Corner: Properties and Dimensions



Stock Width of Blank Taken at $t/3$ Distance From Inner Surface.



Nominal Gauge No.	Thickness t in	Properties: Moment of inertia $I_x = I_y$ in^4	Properties: Centroid coordinates $x = y$ in	Area in^2	Blank width in	Dimensions: Thickness t in	Dimensions: Radius inside R in	Nominal Gauge No.
10	0.135	0.0003889	0.1564	0.05407	0.3652	0.135	0.1875	10
12	0.105	0.0002408	0.1373	0.03958	0.3495	0.105	0.1875	12
14	0.075	0.0000301	0.0829	0.01546	0.1865	0.075	0.0938	14
16	0.060	0.0000193	0.0734	0.01166	0.1787	0.060	0.0938	16
18	0.048	0.0000128	0.0658	0.00888	0.1724	0.048	0.0938	18
20	0.036	0.00000313	0.0464	0.00452	0.1170	0.036	0.0625	20

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Chapter

10

Solid Freeform Fabrication

Solid freeform *fabrication* (SFF) refers to a category of manufacturing processes in which parts are built by depositing one cross-sectional layer of material on top of the next. It is very much like "printing" a succession of slice images one on top of the next so that thickness is gradually built up (Fig. 10.1). Owing to the fact that material is deposited in thin cross-sectional layers, there are typically no concerns about tool collisions, parting lines, undercuts, etc. It is a toolless and fixtureless approach to making parts. Fabricating highly complex geometric shapes via layered manufacturing processes therefore is no more difficult than fabricating simple geometric shapes such as cubes or cylinders. This is evident in Fig. 10.2, which shows a very impressive geometric sculpture designed by artist Bathsheba Grossman (*www.bathsheba.com*). The sculpture was fabricated using ProMetal's Direct Metal Printing process.

Rapid prototyping (RP) and *rapid manufacturing* (RM) are terms that typically are associated with SFF. In both cases, the parts being fabricated are built layer by layer. The distinction lies simply with the end use of the part being produced. RP produces parts that will be used as part of the iterative design process. RM produces a functional end item to be delivered and used by the customer. Note that the end item can be a steel mold or die if the customer is a molding, casting, or stamping shop.

The terms *rapid prototyping* and *rapid manufacturing* can be somewhat misleading owing to the fact that layered processes

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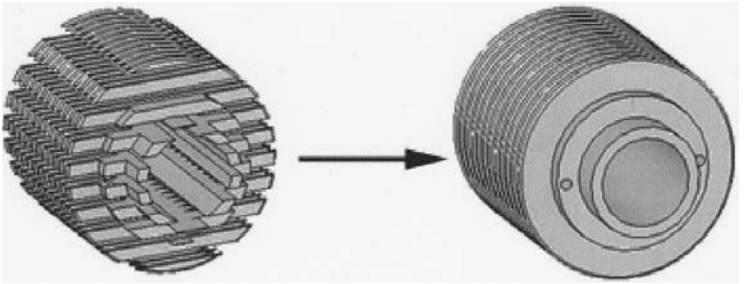

Figure 10.1 Principle of layer-additive manufacturing.

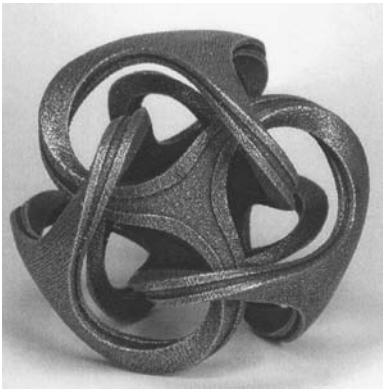

Figure 10.2 Complex freeform structure. *(Photo courtesy of Bathsheba Grossman.)*

generally are much slower than mass-production processes such as die casting or injection molding. However, layered manufacturing processes are capable of building parts with complex geometries much more quickly than generally would be possible when using conventional fabrication techniques. When production quantities are not sufficiently high to justify the expense of tooling and fixturing, then one of the SFF processes can be cost-effective.

The vast majority of early SFF processes were developed to produce nonmetallic parts. Some of the early processes included stereolithography (3D Systems), fused deposition modeling (Stratasys), and selective laser sintering (3D Systems). The SLS process also has been used to make sintered parts from both metal and ceramic powders.

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Solid Freeform Fabrication

More recently, literally dozens of relatively inexpensive layered manufacturing processes have been commercialized. In order to obtain fully dense metal parts from one of these processes, it is generally necessary to use a two-step process in which the prototype part is used as the pattern for a casting or forming process. For example, polymer prototype parts often are used as patterns for investment casting or sand casting.

10.1 Direct-Metal Rapid Manufacturing Processes

Recent years have witnessed a flurry of research and development aimed at "direct-metal" RM processes. These processes are of particular interest to machinists and metalworkers. Rather than using an indirect approach such as investment casting to produce a metal part, these processes directly produce near-net-shape functional metal components.

Owing to the considerable expense usually associated with direct-metal RM processes, they typically are used for one of several reasons.

Material cost. RM processes are selected most often to produce parts from very expensive alloys with special material properties. Because RM processes produce components to near-net shape, very little material is wasted in finish machining. In many cases these materials are quite difficult to machine; hence producing them to near-net shape dramatically speeds up fabrication of the final part and reduces material costs. Although titanium and its alloys (most notably Ti-6Al-4V) seem to have attracted the most interest, there also has been considerable development work involving a wide variety of metal-matrix composites (MMCs) involving TiB, TiC, SiC, and other reinforcements. The majority of RM processes are powder-based, so particulate-reinforced MMCs are employed rather than continuously reinforced MMCs.

Ease of joining. Some alloys are notoriously difficult to join via welding, brazing, or similar thermal methods. With traditional manufacturing methods, it is often the case that components in an assembly are designed as separate pieces merely to accommodate the production method. Because geometric complexity is not a major concern when RM processes are used, it is often possible to merge several parts into one part. In some cases the elimination of assembly joints also can have implications for improved component reliability.

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Design optimization. RM processes can produce complex geometric shapes that would be extremely difficult and/or costly to fabricate via more conventional means. Owing to the fact that the designer need not be concerned with demolding a part or (in some cases) cutting-tool access, it is possible to optimize components for special form or function with little regard for the manufacturing process. Some examples include

Internal wiring. Electrical wiring can be routed through channels that are fabricated in the walls of a part so that the wiring is protected from external moving components.

Conformal cooling channels. Conventional mold/die cooling channels typically lie in a flat plane. With RM, it is possible to fabricate cooling channels that conform to or flow with the actual shape of the core/cavity surfaces in each of the three dimensions. By routing coolant close to the mold/die surface, more uniform cooling can be achieved, thus lowering stresses brought about by uneven cooling. Furthermore, cycle times can be reduced. In addition to having cooling channels that conform to the shape of the tool surface, it is also possible to vary the cross section of the channel itself. It need not be round. For instance, it can fan out to a larger surface area as it passes near the mold surface. Likewise, baffles can be built in to increase turbulence if so desired.

Weight optimization. Through finite element analysis (FEA) codes, mechanical designers are able to determine exactly where material can be removed from a component without adversely affecting the function and safety of a part. However, designing a weight-optimized part and fabricating it are two separate issues. In many instances, an RM method can fabricate optimized components that would be very difficult to fabricate via conventional methods. For this reason, the aerospace, automotive, and military industries have been among the early adopters of these direct-metal technologies. Figure 10.3 shows a geometrically complex component for a head-mounted display. In order to reduce weight, the three "tentacles" coming off the device have been hollowed out.

Compositional optimization. Some RM processes have the ability to independently deposit multiple materials in varying amounts. Much like a printer is able to print thousands of colors with just three or four print heads, these systems can locally vary the material composition of a component to achieve material properties that cannot be had any other way.

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Figure 10.3 Ti-6Al-4V head-mounted display component built via electron-beam melting (EBM). *(CAD design courtesy of Dr. Jannick Rolland, University of Central Florida.)*

10.1.1 Electron-beam melting

Electron-beam melting (EBM) is a process developed by Arcam AB of Sweden (*www.arcam.com*). Alloys such as H13 steel, Ti-6Al-4V, TiAl, and Inconel can be fabricated with this process. A thin layer of metal powder, typically 100 μm thick, is first spread over a plate. An electron-beam gun is selectively scanned over the powder bed with enough power to melt the metal powder that it comes in contact with. The platform is lowered, a new layer of powder is spread, and the process repeats itself. The entire process takes place in vacuum, which helps to prevent unwanted oxidation of metal powders at elevated temperatures. On completion of the final layer, the part is removed from the bed of loose unmelted powder that surrounds it. The unmelted powder surrounding the part also serves to support any downward-facing surfaces.

Parts fabricated via most powder-based RM processes, including EBM, possess textured surfaces somewhat resembling those of sand

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castings. For example, Fig. 10.3 shows an as-processed Ti-6Al-4V head-mounted display component built via EBM prior to finish machining. As is the case with sand castings, critical features are subjected to any necessary finish machining operations. Approximately 0.5 to 1.5 mm of material typically is recommended as a machining allowance. Finish machining of Ti-6Al-4V parts built with this process has been achieved using TiAlN-coated end mills with a cutting speed of 50 ft/min and a feed rate of 0.007 in/tooth. Figure 10.4 shows a finish-machined nozzle component built via the EBM process in the Ti-6Al-4V alloy.

Despite the fact that metal is melted in layers, components fabricated via EBM possess excellent interlayer bonding. The fact that each layer is so thin also means that melt solidification takes place very rapidly, thus leading to a refined microstructure. High-performance materials that are difficult to process, such as titanium aluminide, can be processed via the EBM process owing primarily to the fact that the entire part is kept at an elevated temperature during processing. This significantly reduces thermal stresses that would be caused by depositing molten material on top of (relatively) cold previously solidified material. Thermal stresses generally lead to warping and/or cracking in the workpiece; hence proper thermal management is critical for any of the direct-metal RM processes.

One particularly intriguing aspect of EBM and other direct-metal RM processes is that locating features easily can be built into each component to facilitate finish machining.

Figure 10.4 Finish-machined titanium component. *(Photo courtesy of Arcam AB.)*

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10.1.2 Selective laser sintering (SLS)

3D System's SLS process (*www.3dsystems.com*) is capable of processing a wide variety of polymer, metal, and ceramic powders. Of particular interest to the machinist or metalworker is the LaserForm A6 steel material. The LaserForm material consists of A6 steel particles that have been coated with a polymeric binder. A thin layer of the powder is spread over a platform, and a 100-W (typical) laser scans the cross-sectional area of the first layer to be produced. Heat from the laser causes the polymer binder to melt, thus agglomerating together the metal particles for that layer. The process is repeated one layer after the next until the part is complete. The green polymer-bound part is removed from the powder bed and placed in a furnace. The polymer binder is vaporized under careful control, and the remaining steel particles are sintered. The resulting component is porous sintered A6 steel. If full density is desired, the part can be infiltrated with a secondary metal such as bronze. Figure 10.5 shows a photograph of a well-known rook chess piece that was built in steel and infiltrated with bronze using the SLS process.

Figure 10.5 SLS rook chess piece in bronze-infiltrated tool steel.

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10.1.3 Laser additive manufacturing (LAM)

Rapid prototyping processes based on laser forming generally involve using a high-power laser to start a melt pool. One or more powder feeders then are used to direct metal powder into the melt pool at a predetermined rate. The melt pool typically is shielded with inert gas such as argon to inhibit oxidation. The laser and powder are moved simultaneously above the surface of the substrate, thus producing a moving melt pool into which new powder material is constantly added. Slightly varying versions of laser additive manufacturing processes have been commercialized by Optomec (*www.optomec.com*), Aeromet (*www.aerometcorp.com*), and POM (*www.pomgroup.com*).

A particularly attractive advantage of LAM processes is that multiple powder feeders can be used. By using multiple powder feeders and varying the rate with which each powder is added to the melt pool, it is possible to locally vary the material composition of a component to match its mechanical requirements in service. For instance, the composition of a component might be tailored to provide a tough, fracture-resistant core that is surrounded by a hard, wear-resistant outer skin. Figure 10.6 shows a laser deposition nozzle with multiple powder feeders.

Because there typically is no powder bed surrounding the part(s) being fabricated, production of components with downward-facing surfaces can be a challenge. Systems equipped with three-axis motion controllers can deposit material only on gradually tapered downward-facing surfaces. Surfaces with steeper downward-facing slopes generally must be fabricated on systems equipped with five-axis positioning systems and specialized software to generate material deposition toolpaths that will not result in collisions between the powder feeders and previously deposited materials.

Although fabricating complex geometries with downward-facing surfaces generally is more difficult to accomplish with LAM systems that do not surround the part with powder, LAM systems are very well suited to repairing damaged or worn surfaces on existing parts. Because of their ability to control chemical composition, they are also used to deposit special coatings on existing parts.

10.2 Rapid Tooling

Rapid tooling can be defined in many ways. In the simplest sense, *rapid tooling* refers to the practice of either directly fabricating a tool (mold, die, etc.) from any one of the RM processes or fabricating a tool using an RP/RM component as a pattern.

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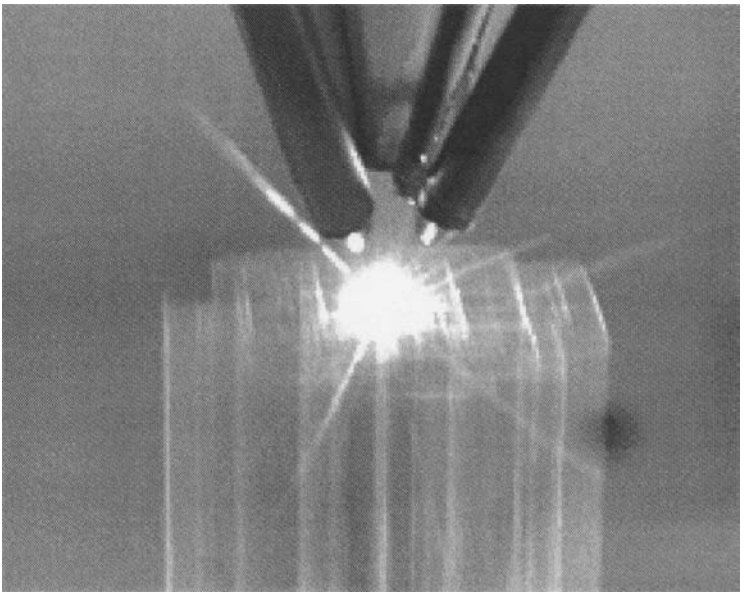

Figure 10.6 Laser-engineered net shaping with multiple powder feed nozzles. *(Photo used with permission of Sandia National Laboratories.)*

10.2.1 RTV silicone molds

One of the most widely used approaches to rapid tooling involves making room-temperature vulcanizing (RTV) silicone molds from a pattern made on any one of the RP/RM processes. The RTV mold may be fabricated in two pieces, or it may be a one-piece cut mold. Regardless of how the RTV mold is made, polyurethane or other two-part resins are then cast into the mold to produce a plastic part. The urethane may include dyes and/or fillers to modify its appearance and material properties. Common fillers include glass beads to reduce part weight and to reduce the volume (and cost) of the resin being used. Chopped fiberglass strands sometimes are added to increase part strength. Metal powders such as bronze are also added at times to make the part look and feel like a metal part. Provided the powder loading is sufficiently high, it is possible to buff the parts in order to achieve a somewhat shiny metallic look. Depending on the resin being cast, the workpiece geometry, and any fillers/additives, the typical RTV mold usually is good for approximately 30 to 50 castings.

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Fabricating One-Piece Cut RTV Molds. The process for fabricating a one-piece cut mold is relatively straightforward.

1. Any of the RP processes is used to fabricate a pattern of the part to be molded. Shrinkage allowance for the resin used must be factored into the pattern dimensions.
2. Visual inspection of the part determines the parting line for the two halves of the mold. Note that the RTV is flexible; hence small to moderate undercut features generally may be molded without difficulty. To aid in cutting the mold apart in a later step, the parting line is often drawn onto the part using a permanent marker.
3. The RP part is suspended by wires and/or pins inside of a box with approximately 25 mm (1 in) of clearance on all sides. Care must be taken to ensure that the part is held firmly in place. When the RTV silicone is poured into the box, a loosely attached part can break free and either float or sink depending on its buoyancy in the RTV silicone. At this point, it is helpful to visually project the parting line from the part out to the walls of the box. A permanent marker is then used to sketch the location of the projected parting line around the perimeter of the box.
4. The RTV silicone rubber is mixed and degassed according to the manufacturer's recommendations and then is poured slowly into the box until the liquid level is approximately 25 mm (1 in) above the top of the part. The box is set aside and allowed to vulcanize (cure) for approximately 24 hours. Note that there are a wide variety of RTV rubbers that vary according to their translucency, hardness, tear strength, etc. It is generally much easier to make one-piece cut molds using clear or somewhat translucent RTV materials than opaque ones.
5. Once the rubber has cured, the walls of the box are removed. A number of knives then are used to cut the rubber down to the parting line of the part. Once the parting line has been located, the knives are used to follow the parting line around the part. Note that a slight zigzag pattern should be cut as the rubber halves are separated. Doing so will provide self-interlocking features so that the reassembled mold halves will align properly during casting.
6. Once the mold is cut apart, the RP pattern is removed, thus leaving a cavity in the rubber mold.

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7. The knife is used to cut a pouring basin into the rubber, along with any vent channels that may be needed. The urethane generally is poured into the highest point on the part. It is helpful to visualize the urethane filling up the mold. Air vents should be cut into the mold at any locations where air is likely to become trapped during the filling process.

Fabricating Two-Piece RTV Molds. The process for fabricating a two-piece RTV mold is only slightly more complicated than that used to make one-piece cut molds.

1. Any of the RP processes is used to fabricate a pattern of the part to be molded. Shrinkage allowance for the resin used must be factored into the pattern dimensions.
2. Visual inspection of the part determines the parting line for the two halves of the mold. The part is then embedded in modeling clay or a similar material. Various hand tools are used to build the clay up to the parting line for the part. At this point, the upper half of the part protrudes above the clay along the parting line.
3. The clay-supported pattern is then placed inside a box. A suitable release agent is sprayed on the exposed part, clay, and inner box walls.
4. The RTV silicone rubber is mixed and degassed according to the manufacturer's recommendations and then is poured slowly onto the exposed part and clay surface until the liquid level is approximately 25 mm (1 in) above the top of the part. The box is set aside and is allowed to vulcanize (cure) for approximately 24 hours.
5. The following day, the box is flipped over, and the clay that that part was embedded in from beneath is removed. At this point, the upper half of the part is now embedded in the cured RTV silicone.
6. A knife is used to cut pyramidal (or other) chunks of cured RTV silicone away around the perimeter of the part. When the second batch of RTV is poured, this will lead to the formation of interlocking features that keep the two mold halves aligned.
7. The exposed part and RTV silicone surfaces are sprayed with a suitable release agent.

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8. A second batch of RTV silicone rubber is mixed and poured over the exposed part and RTV surfaces. This is allowed to cure for approximately 24 hours.
9. Once the rubber has cured, the walls of the box are removed. Provided an appropriate release agent has been used, the two cured halves of RTV silicone should just peel apart along the parting line without any need to cut them with a knife.
10. The RP pattern is removed, thus leaving a cavity in the rubber mold.
11. The knife is used to cut a pouring basin into the rubber along with any vent channels that may be needed.

Casting the Polyurethane

1. Regardless of which type of mold has been produced, all mold surfaces are sprayed with a release agent that has been matched to the urethane being cast. The mold halves then are clamped together between a pair of flat boards. Hand clamps or even rubber bands can be used to hold the assembled mold together. Since the RTV rubber is compressible, care must be taken to avoid distorting the cavity when the mold halves are clamped.
2. The urethane and any colorants/fillers/etc. are mixed together and poured slowly into the cavity. Once the urethane has hardened (generally 1 to 15 minutes depending on the urethane formulation), the mold is opened up, and the part is removed.
3. The process can be repeated until the polyurethane begins to stick to the mold despite the use of a mold releasing agent.

   Caution: Be sure to follow the polyurethane manufacturer's recommended safety precautions regarding proper ventilation as well as skin and eye protection. Many of the uncured polyurethane compounds are considered carcinogenic. Also take note of the fact that the reaction taking place during curing is exothermic. The amount of heat released can be sufficient to burn skin in some cases.

10.2.2 Direct-inject stereolithography tooling

Direct-inject SLA tooling refers to the practice of using photosensitive resins with the stereolithography process (*www.3dsystems.com*) to

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produce an injection-mold insert. The insert goes into a mold base in an injection-molding press. SLA tools are not intended for production use, but they are a fast and relatively inexpensive way to produce mold inserts that can be used to injection-mold small batches of functional plastic parts in the desired resin. Depending on the melting temperature of the resin being injected and the presence or absence of fillers (e.g., glass-filled nylon), direct-inject tooling may last from just a few shots to several hundred shots.

When the molded part has complex geometry, it is customary to produce a "hand mold." Rather than assembling a complex tool with hydraulic slides and other moving components, the direct-inject inserts with removable cores are assembled by hand and placed in the mold base. The inserts are then removed from the mold base following each shot, and the cores are removed from the part by hand. The tooling then is reassembled, and the next shot is made. This is obviously not a suitable approach for mass production, but it is quite feasible to produce tens or even hundreds of sample plastic parts by this method.

Figure 10.7 shows a close-up photograph of a direct-inject six-cavity SLA insert used to mold miniature worm gears. The mating insert is not shown in the photograph because it is nearly identical to the one shown in Fig. 10.7. Each insert is 35 mm (1⅜ in) square and 9.5 mm (⅜ in) deep. It took approximately 1 hour of machine time to fabricate this pair of inserts on a high-resolution stereolithography machine without any need to program computer numerical

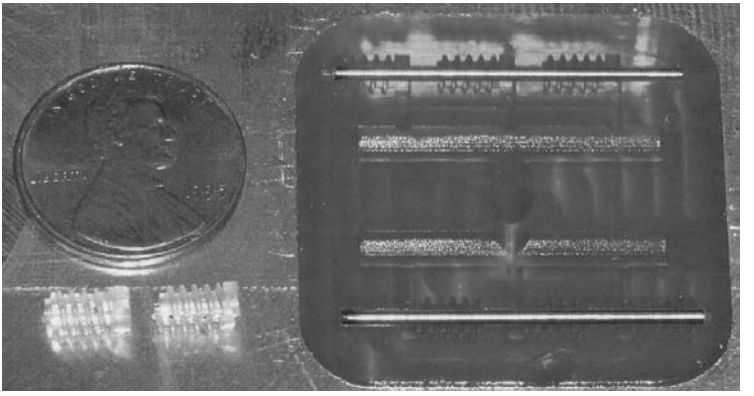

Figure 10.7 Direct-inject SLA inserts for molding worm gears.

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control (CNC) toolpaths or to design an electrode. A steel pin insert is placed in the mold prior to injection, and the worms are slid off the pin following injection. The worms are approximately 6 mm long, with a diameter of just under 3 mm. A pair of molded worms is shown in the lower left of the photograph. The penny is included simply to provide the reader with an idea of the scale involved.

10.2.3 Electroplated prototypes

For instances where it is helpful to have metal-like parts that do not necessarily need the same material properties as a final production metal part, it is possible to electroplate prototype components. Chapter 13 provides details on various plating processes, although plating nonconducting polymer components can be tricky.

A simple though not terribly reliable approach to obtaining an electrically conducting surface on the plastic prior to electroplating is to manually paint it with conductive paints. Paints containing silver or copper powders are readily available for this purpose. This approach will work in simple cases, but the adhesion of the paint to the plastic surface during subsequent electroplating is often inadequate. The result is blistering or flaking of the plated surface.

A more reliable approach to preparing plastics for plating is as follows: First, the components to be plated must be completely cleaned of any oils, solvents, etc. In order to improve adhesion of the plating to the plastic, the surface of the plastic often is etched in a chromic acid bath. Next, the surfaces of the parts are sensitized through the addition of a palladium chloride solution. This step allows palladium metal to deposit on the etched surface of the plastic. Either electroless nickel or copper coatings may then be applied, with the palladium acting as a catalyst for nickel or copper deposits. A very thin ($\leq$1 μm) electroless nickel coating is common. At this point, the surface of the plastic has been made to be electrically conducting with reasonably good adhesion properties. The surface then can be electroplated using techniques described in Chap. 13. When the part is to undergo mechanical stress, a copper plating often is recommended prior to nickel plating. Nickel platings can be followed by a chrome plate if desired for aesthetic purposes.

Many electroplating compounds are highly toxic and are highly regulated. Consequently, prototype plastic parts often are sent out to specialty shops for plating. Figure 10.8 shows a batch of complex

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Figure 10.8 SLArmor air pump components. *(Photo courtesy of Fineline Prototyping, Inc.)*

handheld air compressor components that were fabricated in a DSM Somos Prototool material on a high-resolution stereolithography machine by Fineline Prototyping, Inc. The parts then were given a proprietary SLArmor coating that consists primarily of a copper strike coat followed by an electroless nickel plating. With minimal hand finishing, these components were assembled into a fully functional handheld air compressor.

10.2.4 Investment casting via 3D printing

Three-dimensional (3D) printing is a process that was developed at the Massachusetts Institute of Technology (MIT) and subsequently brought to market by several companies, including Z Corporation, ExtrudeHone, Soligen, and Therics. Z Corporation has introduced a special powder and binder formulation for fabricating investment casting shells. The company refers to this process as *ZCast*. At the present time, it is used for casting nonferrous alloys such as zinc or aluminum. As is the case with many RP processes, Z Corporation's version of 3D printing starts by spreading a thin layer of powder. In this case, the powder being spread is a specially formulated casting investment. An inkjet print system is then scanned across the powder bed. The printer prints an image of the current cross-sectional slice of the investment casting shell being produced. The moisture in the ink is the binder that causes the casting investment to

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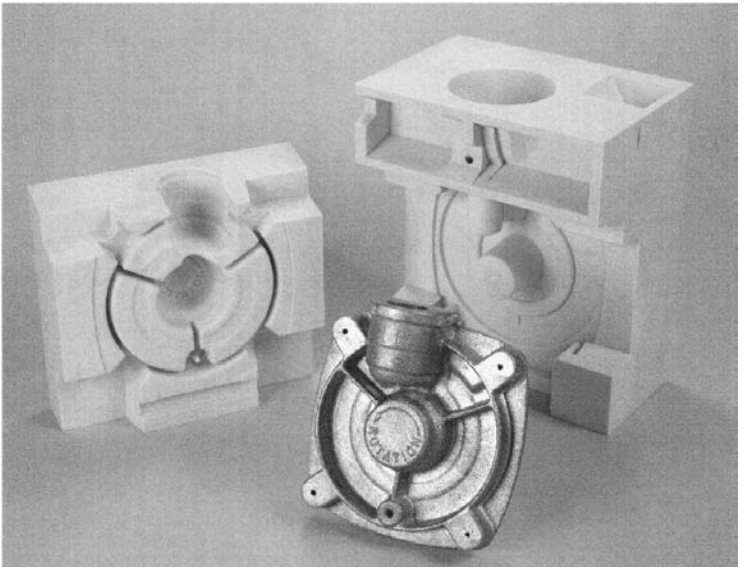

Figure 10.9 ZCast cover with mold. *(Photo courtesy of ZCorp.)*

harden. This is akin to mixing water with plaster, except on a much smaller scale. This process is used to fabricate the shell in two pieces, as well as any cores that are needed. Figure 10.9 shows a completed cover housing along with the ZCast tooling needed to produce such a casting.

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Chapter

11

Hardening and Tempering Steels and Nonferrous Alloys

The hardening and tempering of steels and nonferrous alloys are important aspects of metalworking. Carbon and alloy steels are relied on to perform a great number of services in the metalworking industries. Some of the nonferrous metals and alloys are also capable of being hardened above their normal condition either through heat treatment or cold working and find countless uses in product design and manufacturing.

11.1 Standard Steels and Steel-Making Practices

Steel is the generic name for a large group of iron-carbon alloys. The basic materials used in steel making are iron ore, coke, and limestone. A blast furnace converts these materials into a product known as *pig iron,* which contains considerable amounts of carbon, manganese, sulfur, phosphorus, and silicon. Basic oxygen furnaces are also employed in steel making, as are other methods. Steel making's basic constituent, pig iron, is hard and brittle and unsuitable for processing into usable wrought iron or steel products. Steel making is the process of refining pig iron and iron and steel scrap by removing unwanted elements and adding the desirable elements in predetermined and controlled amounts. Most steel-making processes cause a combination of carbon and oxygen to form a gas. When a steel is

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deoxidized strongly with a deoxidizing agent, no gas forms, and the steel is called *killed steel.* The degree of deoxidation affects some of the properties of the steel, and the degree of gas evolution characterizes steels that are known as *semikilled, capped,* and *rimmed.* In addition to oxygen, fused steel contains small amounts of hydrogen and nitrogen. Special deoxidation practices, including vacuum treatment, may be used to control the amount of dissolved gases in the steel.

The carbon content of the common steel grades ranges from a few hundredths of 1 percent to 0.95 percent. All common steels contain manganese, sulfur, phosphorus, and silicon to some degree.

Wrought steels are the most common and widely used engineering materials. There is no other single material that offers such a broad range of practical applications as the various types and grades of steels.

The unified numbering system for steels is shown in Chap. 4, "Materials and Their Uses." This system classifies the various types of steels and provides identification numbers.

11.2 Constituents of Steel: Phases

When carbon steels are heated to various temperatures, changes take place in the structure that are known as *phases.* Figure 11.1 is a diagram showing the relationship between temperature and the amount of carbon in the steel that affects the basic structure. The diagram is presented strictly for academic reasons and serves the purpose of describing the different states that the steel assumes when the temperature and carbon content are varied. The actions and reactions that occur during the heating and cooling of carbon and alloy steels are complex and form the basis for the controlled heat treatments that are performed on the various types of steels.

The diagram in Fig. 11.1 indicates the phase transformations that occur in steels with up to 6.67 percent carbon content, where the main form of the steel above 2066°F is called *cementite.* The other forms or states/phases are indicated by the various letters and combinations of letters shown below the figure. Some of the other forms that occur are shown below the letter designations, the most important of which is *martensite.* Martensite is the phase or form of carbon steel that is produced in the hardening process, which will be described in a later section.

Carbon steels with less than 0.85 percent carbon are called *hypoeutectoid,* and those with carbon contents greater than 0.85

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Hardening and Tempering Steels and Nonferrous Alloys

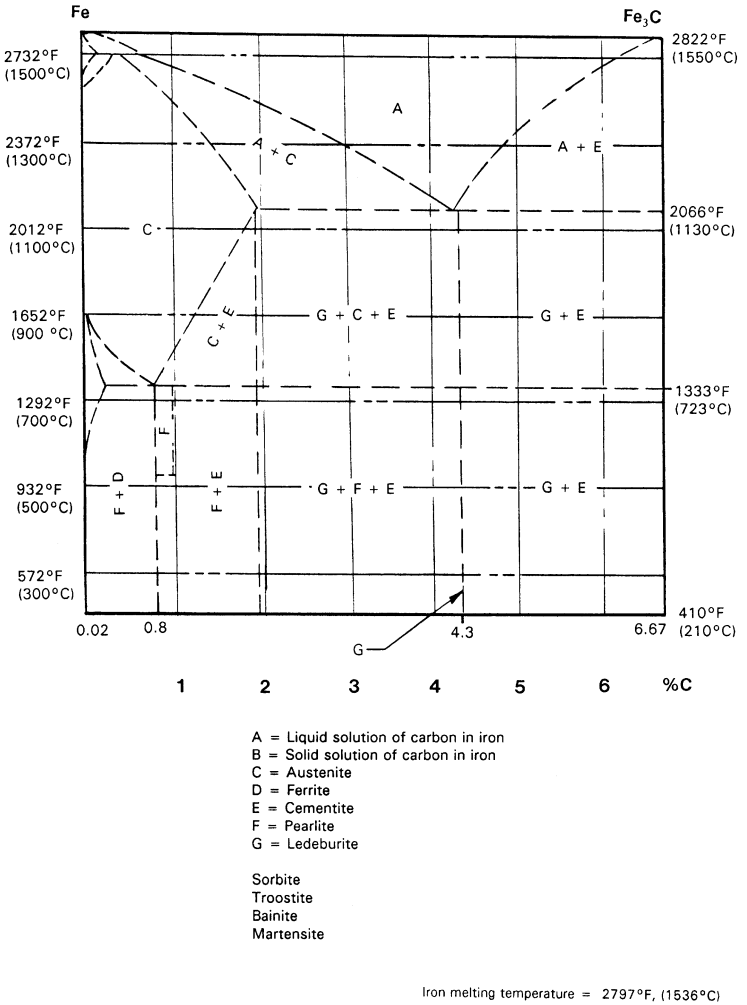

Figure 11.1 Iron, iron-carbide diagram.

percent are called *hypereutectoid.* In binary-alloy systems, a *eutectoid alloy* is a mechanical mixture of two phases that form simultaneously from a solid solution when it cools through the eutectoid temperature. Alloys leaner or richer in one of the constituents or metals undergo transformation from the solid-solution phase over

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a range of temperatures beginning above and ending at the eutectoid temperature. The structure of such alloys will consist of primary particles of one of the stable phases in addition to the eutectoid, e.g., ferrite and pearlite in low-carbon steel.

11.3 Standard Definitions of Terms Pertaining to Heat Treatment of Metals

Many terms are associated with the heat treatment of metals, and the American Society for Testing and Materials (ASTM) has classified these terms in ASTM Standard E44-84. Figure 11.2 outlines the terms and definitions as described in ASTM Standard E44-84 and is reproduced with permission from the ASTM.

By studying the diagram shown in Fig. 11.1 and the definitions of terms in Fig. 11.2, you will gain an excellent insight into the practice of heat treatment of metals.

11.4 Heat Treatment of Steels

In fully annealed carbon steels, the percentage of carbon determines the structural constitution of the steel. Figure 11.1 shows the constitution or phases for varying carbon content versus temperature.

Effect of heating fully annealed carbon steels. When fully annealed carbon steels are heated above the lower critical point, which ranges between 1335 and 1355°F, depending on the carbon content, austenite is formed. If the temperature continues to rise, the steel structure will change completely to austenite. The temperature at which excess ferrite and cementite are completely dissolved in the austenite is called the *upper critical point.* This critical temperature varies with the carbon content of the steel. If the steel is cooled slowly to ambient temperature, the steel returns to its original condition.

Effect of rapid cooling or quenching carbon steels. Simply stated, when carbon steels are heated to a certain temperature, suddenly cooling the steel at the proper cooling rate causes the austenite to transform to martensite, which has very high hardness. Thus the operation of hardening steels consists of two steps. The first step is to heat the steel at least 100°F higher than its transformation point, and the second step is to cool the steel at some rate that is

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Hardening and Tempering Steels and Nonferrous Alloys

faster than the critical rate. (The *critical rate* is determined by or depends on the carbon content and alloying elements present in the steel.) The hardness of a martensitic steel depends on its carbon content and ranges from 460 Brinell at 0.20 percent carbon to 710 Brinell at 0.50 percent carbon. Ferrite has a hardness of approximately 90 Brinell, pearlite approximately 240 Brinell, and cementite approximately 550 Brinell.

Standard Definitions of Terms Relating to Heat Treatment of Metals
ASTM E44-84

(Temperatures have been omitted from these definitions, which are not intended as specifications)

Ac_{cm}, Ac_1, Ac_3, Ac_4—See **transformation temperature.**

age hardening—hardening by aging, usually after rapid cooling or cold working. See **aging.**

aging—a change in the properties of certain metals and alloys that occurs at ambient or moderately elevated temperatures after hot working or a heat treatment (quench aging in ferrous alloys, natural or artificial aging in ferrous and nonferrous alloys) or after a cold-working operation (strain aging). The change in properties is often, but not always, due to a phase change (precipitation), but never involves a change in chemical composition of the metals or alloys. See also **age hardening, artificial aging, natural aging, overaging, precipitation hardening, precipitation heat treatment, progressive aging, quench aging,** and **strain aging.**

annealing—heating to and holding at a suitable temperature and then cooling at a suitable rate, for such purposes as reducing hardness, improving machinability, facilitating cold working, producing a desired microstructure, or obtaining desired mechanical, physical, or other properties. When applicable, the following more specific terms should be used:

black annealing
blue annealing
box annealing
bright annealing
flame annealing
full annealing
graphitizing
intermediate annealing
isothermal annealing
malleableizing
process annealing
quench annealing
recrystallization annealing
spheroidizing

Definitions of the above terms are given below in their alphabetic positions.

When applied to ferrous alloys, the term "annealing," without qualification, implies full annealing.

When applied to nonferrous alloys, the term "annealing" implies a heat treatment designed to soften a cold-worked structure by recrystallization or subsequent grain growth or to soften an age-hardened alloy by causing a nearly complete precipitation of the second phase in relatively coarse form.

Any process of annealing will usually reduce stresses but if the treatment is applied for the sole purpose of such relief it should be designated **stress relieving.**

Ar_{cm}, Ar_1, Ar_3, Ar_4—See **transformation temperature.**

artificial aging—aging above room temperature. See **aging** and **precipitation heat treatment.** Compare with **natural aging.**

austempering—quenching a ferrous alloy from a temperature above the transformation range in a medium having a rate of heat abstraction high enough to prevent the formation of high-temperature transformation products, and then holding the alloy, until transformation is complete, at a temperature below that of pearlite formation and above that of martensite formation.

austenitizing—forming austenite by heating a ferrous alloy into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing).

baking—heating to a low temperature in order to remove gases.

black annealing—box annealing or pot annealing ferrous alloy sheet, strip, or wire. See **box annealing.**

blank carburizing—simulating the carburizing operation without introducing carbon. This is usually accomplished by using an inert material in place of the carburizing agent, or by applying a suitable protective coating to the ferrous alloy.

blank nitriding—simulating the nitriding operation without introducing nitrogen. This is usually accomplished by using an inert material in place of the nitriding agent, or by applying a suitable protective coating to the ferrous alloy.

blue annealing—heating hot-rolled ferrous sheet in an open furnace to a temperature within the transformation range and then cooling in air, in order to soften the metal. The formation of a bluish oxide on the surface is incidental.

bluing—subjecting the scale-free surface of a ferrous alloy to the action of air, steam or other agents at a suitable temperature, thus forming a thin blue film of oxide and improving the appearance and resistance to corrosion.

[1] These definitions are under the jurisdiction of ASTM Committee A-1 on Steel, Stainless Steel, and Related Alloys and are the direct responsibility of Subcommittee A1.92 on Terminology.

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Figure 11.2 Standard terms relating to the heat treatment of metals. *(Reprinted with permission from the Annual Book of ASTM Standards, copyright 1992, American Society for Testing and Materials.)*

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Hardening and Tempering Steels and Nonferrous Alloys

NOTE—This term is ordinarily applied to sheet, strip, or finished parts. It is used also to denote the heating of springs after fabrication, in order to improve their properties.

box annealing—annealing a metal or alloy in a sealed container under conditions that minimize oxidation. In box annealing a ferrous alloy, the charge is usually heated slowly to a temperature below the transformation range, but sometimes above or within it, and is then cooled slowly; this process is also called "close annealing" or "pot annealing." See **black annealing.**

bright annealing—annealing in a protective medium to prevent discoloration of the bright surface.

burning (burnt, burned)—a term applied to metal which has been permanently damaged by having been heated to a temperature close to or within the melting range. This results in a structure exhibiting incipient melting or intergranular oxidation.

carbonitriding—a case hardening process in which a suitable ferrous material is heated above the lower transformation temperature in a gaseous atmosphere of such composition as to cause simultaneous absorption of carbon and nitrogen by the surface and, by diffusion, create a concentration gradient. The process is completed by cooling at a rate that produces the desired properties in the workpiece.

carbon potential—a measure of the ability of an environment containing active carbon to alter or maintain, under prescribed conditions, the carbon content of the steel.

NOTE—In any particular environment, the carbon level attained will depend on such factors as temperature, time, and steel composition.

carbon restoration—replacing the carbon lost in the surface layer from previous processing by carburizing this layer to substantially the original carbon level.

carburizing—a process in which an austenitized ferrous material is brought into contact with a carbonaceous atmosphere of sufficient carbon potential to cause absorption of carbon at the surface and by diffusion, create a concentration gradient.

case—*in a ferrous alloy*, the outer portion that has been made harder than the inner portion (see **core**) as a result of altered composition, or structure, or both, from treatments such as carburizing, nitriding, and induction hardening.

case hardening—a generic term covering several processes applicable to steel that change the chemical composition of the surface layer by absorption of carbon, nitrogen, or a mixture of the two and, by diffusion, create a concentration gradient. The processes commonly used are: **carburizing** and **quench hardening**; **cyaniding**; **nitriding**; and **carbonitriding.** The use of the applicable specific process name is preferred.

cementation—the introduction of one or more elements into the outer portion of a metal object by means of diffusion at high temperature.

close annealing—See **box annealing.**

cold treatment—exposing to subzero temperatures for the purpose of obtaining desired conditions or properties, such as dimensional or structural stability. When the treatment involves transformation of retained austenite, it is usually followed by a tempering treatment.

conditioning heat treatment—a preliminary heat treatment used to prepare a material for a desired reaction to a subsequent heat treatment. For the term to be meaningful, the exact treatment must be specified.

controlled cooling—cooling from an elevated temperature in a predetermined manner to avoid hardening, cracking, or internal damage or to produce a desired microstructure or mechanical properties.

core—(*1*) *case hardening*—interior portion of unaltered composition, or microstructure, or both, of a case-hardened steel article.

(*2*) *clad products*—the central portion of a multilayer composite metallic material.

critical cooling rate—the minimum rate of continuous cooling to prevent undesirable transformations. For steel, unless otherwise specified, it is the slowest rate at which austenite can be cooled from above critical temperature to prevent its transformation above the M_s temperature.

critical temperature range—synonymous with **transformation range.** The term is of historic significance only, and its use is discouraged.

cyaniding—introducing carbon and nitrogen into a solid ferrous alloy by holding above Ac_1 in contact with molten cyanide of suitable composition. The cyanided alloy is usually quench hardened.

cycle annealing—an annealing process employing a predetermined and closely controlled time-temperature cycle to produce specific properties or microstructure.

decarburization—the loss of carbon from the surface of a ferrous alloy as a result of heating in a medium that reacts with the carbon.

differential heating—heating that intentionally produces a temperature gradient within an object such that, after cooling, a desired stress distribution or variation in properties is present within the object.

diffusion coating—any process whereby a basis metal or alloy is either: (*1*) coated with another metal or alloy and heated to a sufficient temperature in a suitable environment, or (*2*) exposed to a gaseous or liquid medium containing the other metal or alloy, thus causing diffusion of the coating or of the other metal or alloy into the basis metal with resultant change in the composition and properties of its surface.

direct quenching—quenching carburized parts directly from the carburizing operation.

double aging—employment of two different aging treatments to control the type of precipitate formed from a supersaturated alloy matrix in order to obtain the desired properties. The first aging treatment, sometimes referred to as intermediate or stabilizing, is usually carried out at a higher temperature than the second.

double tempering—a treatment in which quench-hardened steel is given two complete tempering cycles at substantially the same temperature for the purpose of assuring completion of the tempering reaction and promoting stability of the resulting microstructure.

drawing—a misnomer for **tempering.**

ferritizing anneal—the process of producing a predominantly ferritic matrix in a ferrous alloy through an appropriate heat treatment.

flame annealing—annealing in which the heat is applied directly by a flame.

Figure 11.2 (*Continued*)

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flame hardening—a surface hardening process in which only the surface layer of a suitable workpiece is heated by a suitably intense flame to above the upper transformation temperature and immediately quenched.

fog quenching—quenching in a mist.

full annealing—annealing a ferrous alloy by austenitizing and then cooling slowly through the transformation range. The austenitizing temperature for hypoeutectoid steel is usually above Ac_3 and for hypereutectoid steel usually between Ac_1 and Ac_{cm}.

gas cyaniding—a misnomer for **carbonitriding.**

grain growth—an increase in the grain size of a metal, usually as a result of heating at an elevated temperature.

grain size—the dimensions of the grains or crystals in a polycrystalline metal exclusive of twinned regions and subgrains when present. Grain size is usually estimated or measured on the cross section of an aggregate of grains. Common units are: (*1*) average diameter, (*2*) average area, (*3*) number of grains per linear unit, (*4*) number of grains per unit area, and (*5*) number of grains per unit volume. See Methods E 112, for Determining The Average Grain Size.[2]

(*1*) ASTM grain size number—a grain size designation bearing a relationship to average intercept distance at 100 diameters magnification according to the equation: G = ASTM Grain Size Number = $10.00 - 2 \log_2 \bar{L}$, where $\bar{L}$ is the average intercept distance in millimetres at 100 diameters magnification.

(*2*) average grain diameter—the mean diameter of an equiaxed grain section whose size is representative of all the grain sections in the aggregate being measured.

graphitizing—annealing a ferrous alloy in such a way that some or all of the carbon is precipitated as graphite.

hardenability—in a ferrous alloy, the property that determines the depth and distribution of hardness induced by quenching.

hardening—increasing the hardness by suitable treatment, usually involving heating and cooling. When applicable, the following more specific terms should be used: **age hardening, case hardening, flame hardening, induction hardening, precipitation hardening,** and **quench hardening.**

heat treatment—heating and cooling a solid metal or alloy in such a way as to obtain desired conditions or properties. Heating for the sole purpose of hot working is excluded from the meaning of this definition.

homogeneous carburizing—a process that converts a low-carbon ferrous alloy to one of substantially uniform and higher carbon content throughout the section, so that a specific response to hardening may be obtained.

homogenizing—holding at high temperature to eliminate or decrease chemical segregation by diffusion.

hot-cold working—mechanical deformation of austenitic and precipitation hardening alloys at a temperature just below the recrystallization range to increase the yield strength and hardness by either plastic deformation or precipitation hardening effects induced by plastic deformation, or both.

hot quenching—an imprecise term used to cover a variety of quenching procedures in which a quenching medium is maintained at a prescribed temperature above 160°F (71°C).

induction hardening—a surface hardening process in which only the surface layer of a suitable ferrous workpiece is heated by electrical induction to above the upper transformation temperature and immediately quenched.

induction heating—heating by electrical induction.

intermediate annealing—annealing wrought metals at one or more stages during manufacture and before final thermal treatment.

interrupted aging—aging at two or more temperatures, by steps, and cooling to room temperature after each step. See **aging** and compare with **progressive aging.**

interrupted quenching—quenching in which the metal object being quenched is removed from the quenching medium while the object is at a temperature substantially higher than that of the quenching medium. See also **time quenching.**

isothermal annealing—austenitizing a ferrous alloy and then cooling to and holding at a temperature at which austenite transforms to a relatively soft ferrite-carbide aggregate.

isothermal transformation—a change in phase at any constant temperature.

malleableizing—a process in which the ascast malleable-type (white) iron is thermally treated for the purpose of converting most or all of the carbon in Fe_3C to graphite (temper carbon) to produce a family of products with improved ductility.

maraging—a precipitation hardening treatment applied to a special group of iron-base alloys to precipitate one or more intermetallic compounds in a matrix of essentially carbon-free martensite.

NOTE—The first developed series of maraging steels contained, in addition to iron, more than 10 % nickel and one or more supplemental hardening elements. In this series, the aging is done at approximately 900°F (482°C).

martempering—quenching an austenitized ferrous alloy in a medium at a temperature in the upper part of the martensite range, or slightly above that range, and holding in the medium until the temperature throughout the alloy is substantially uniform. The alloy is then allowed to cool in air through the martensite range.

martensite range—the temperature interval between M_s and M_f.

M_f—See **transformation temperature.**

M_s—See **transformation temperature.**

natural aging—spontaneous aging of a super-saturated solid solution at room temperature. See **aging** and compare with **artificial aging.**

nitriding—introducing nitrogen into a solid ferrous alloy by holding at a suitable temperature (below Ac_1 for ferritic steels) in contact with a nitrogenous material, usually ammonia or molten cyanide of appropriate composition. Quenching is not required to produce a hard case.

normalizing—heating a ferrous alloy to a suitable temperature above the transformation range and then cooling in air to a temperature substantially below the transformation range.

Figure 11.2 (*Continued*)

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overaging—aging under conditions of time and temperature greater than those required to obtain maximum change in a certain property, so that the property is altered in the direction of the initial value. See **aging.**

overheating—(*1*)*in ferrous alloys*, heating to an excessively high temperature such that the properties/structure undergo modification. The resulting structure is very coarse-grained. Unlike burning, it may be possible to restore the original properties/structure by further heat treatment or mechanical working, or a combination thereof.

(*2*) in aluminum alloys, overheating produces structures that show areas of resolidified eutectic or other evidence that indicates the metal has been heated within the melting range.

patenting—in wire making, a heat treatment applied to medium-carbon or high-carbon steel before the drawing of wire or between drafts. This process consists in heating to a temperature above the transformation range and then cooling to a temperature below Ae_1 in air or in a bath of molten lead or salt.

postheating—heating weldments immediately after welding, for tempering, for stress relieving, or for providing a controlled rate of cooling to prevent formation of a hard or brittle structure.

pot annealing—See **box annealing.**

precipitation hardening—hardening caused by the precipitation of a constituent from a supersaturated solid solution. See also **age hardening** and **aging.**

precipitation heat treatment—artificial aging in which a constituent precipitates from a supersaturated solid solution. See **artificial aging, interrupted aging,** and **progressive aging.**

preheating—heating before some further thermal or mechanical treatment. For tool steel, heating to an intermediate temperature immediately before final austenitizing. For some nonferrous alloys, heating to a high temperature for a long time in order to homogenize the structure before working.

process annealing—in the sheet and wire industries, heating a ferrous alloy to a temperature close to, but below, the lower limit of the transformation range and then cooling, in order to soften the alloy for further cold working.

progressive aging—aging by increasing the temperature in steps or continuously during the aging cycle. See **aging** and compare with **interrupted aging.**

pseudocarburizing—See **blank carburizing.**

pseudonitriding—See **blank nitriding.**

quench aging—aging induced by rapid cooling after **solution heat treatment.**

quench annealing—annealing an austenitic ferrous alloy by **solution heat treatment.**

quench hardening—hardening a ferrous alloy by austenitizing and then cooling rapidly enough so that some or all of the austenite transforms to martensite. The austenitizing temperature for hypoeutectoid steels is usually above Ac_3 and for hypereutectoid steels usually between Ac_1 and Ac_{cm}.

quenching—rapid cooling. When applicable, the following more specific terms should be used: **direct quenching, fog quenching, hot quenching, interrupted quenching, selective quenching, spray quenching,** and **time quenching.**

recrystallization—the formation of a new grain structure through nucleation and growth commonly produced by subjecting a metal, which may be strained, to suitable conditions of time and temperature.

recrystallization annealing—annealing cold-worked metal to produce a new grain structure without phase change.

recrystallization temperature—the approximate minimum temperature at which recrystallization of a cold worked metal occurs within a specified time.

secondary hardening—the hardening phenomenon that occurs during high-temperature tempering of certain steels containing one or more carbide-forming alloying elements. Up to an optimum combination of tempering time and temperature, the reaction results either in the retention of hardness or an actual increase in hardness.

selective heating—intentionally heating only certain portions of an object.

selective quenching—quenching only certain portions of an object.

shell hardening—a surface hardening process in which a suitable steel workpiece, when heated through and quench hardened, develops a martensitic layer or shell that closely follows the contour of the piece and surrounds a core of essentially pearlitic transformation product. This result is accomplished by a proper balance between section size, steel hardenability, and severity of quench.

slack quenching—the incomplete hardening of steel due to quenching from the austenitizing temperature at a rate slower than the *critical cooling rate* for the particular steel, resulting in the formation of one or more transformation products in addition to martensite.

snap temper—a precautionary interim stress-relieving treatment applied to high-hardenability steels immediately after quenching to prevent cracking because of delay in tempering them at the prescribed higher temperature.

soaking—prolonged holding at a selected temperature.

solution heat treatment—heating an alloy to a suitable temperature, holding at that temperature long enough to cause one or more constituents to enter into solid solution and then cooling rapidly enough to hold these constituents in solution.

spheroidizing—heating and cooling to produce a spheroidal or globular form of carbide in steel. Spheroidizing methods frequently used are:

(*1*) Prolonged holding at a temperature just below Ae_1.

(*2*) Heating and cooling alternately between temperatures that are just above and just below Ae_1.

(*3*) Heating to a temperature above Ae_1 or Ae_3 and then cooling very slowly in the furnace or holding at a temperature just below Ae_1.

(*4*) Cooling at a suitable rate from the minimum temperature at which all carbide is dissolved, to prevent the re-formation of a carbide network, and then reheating in accordance with method (*1*) or (*2*) above. (Applicable to hypereutectoid steel containing a carbide network.)

spinodal decomposition—mechanism of a phase separation from a solid solution into two homogeneous phases of different chemical composition, each having the same crystal structure as the parent metal.

spray quenching—quenching in a spray of liquid.

Figure 11.2 (*Continued*)

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stabilizing treatment—any treatment intended to stabilize the structure of an alloy or the dimensions of a part.

(*1*) heating austenitic stainless steels that contain titanium, columbium, or tantalum to a suitable temperature below that of a full anneal in order to inactivate the maximum amount of carbon by precipitation as a carbide of titanium, columbium, or tantalum.

(*2*) transforming retained austenite in parts made from tool steel.

(*3*) precipitating a constituent from a non-ferrous solid solution to improve the workability, to decrease the tendency of certain alloys to age harden at room temperature, or to obtain dimensional stability.

strain aging—aging induced by cold working. See **aging.**

stress relieving—heating to a suitable temperature, holding long enough to reduce residual stresses and then cooling slowly enough to minimize the development of new residual stresses.

surface hardening—a generic term covering several processes applicable to a suitable ferrous alloy that produces by quench hardening only, a surface layer that is harder or more wear resistant than the core. There is no significant alteration of the chemical composition of the surface layer. The processes commonly used are induction hardening, flame hardening, and shell hardening. Use of the applicable specific process name is preferred.

temper brittleness—brittleness that results when certain steels are held within, or are cooled slowly through, a certain range of temperature below the transformation range. The brittleness is revealed by notched-bar impact tests at or below room temperature.

tempering—(*1*) reheating a quench hardened or normalized ferrous alloy to a temperature below the transformation range (Ac_1), and then cooling at any desired rate. (*2*) a term used in conjunction with a qualifying adjective to designate the relative properties of a particular metal or alloy induced by cold work or heat treatment, or both.

time quenching—interrupted quenching in which the duration of holding in the quenching medium is controlled.

transformation ranges or **transformation temperature ranges**—those ranges of temperature within which austenite forms during heating and transforms during cooling. The two ranges are distinct, sometimes overlapping but never coinciding. The limiting temperatures of the ranges depend on the composition of the alloy and on the rate of change of temperature, particularly during cooling. See **transformation temperature.**

transformation temperature—the temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range. The following symbols are used for iron and steels:

Ac_{cm}—in hypereutectoid steel, the temperature at which the solution of cementite in austenite is completed during heating.

Ac_1—the temperature at which austenite begins to form during heating.

Ac_3—the temperature at which transformation of ferrite to austenite is completed during heating.

Ac_4—the temperature at which austenite transforms to delta ferrite during heating.

Ae_1, Ae_3, Ae_{cm}, Ae_4—the temperatures of phase changes at equilibrium.

Ar_{cm}—in hypereutectoid steel, the temperature at which precipitation of cementite starts during cooling.

Ar_1—the temperature at which transformation of austenite to ferrite or to ferrite plus cementite is completed during cooling.

Ar_3—the temperature at which austenite begins to transform to ferrite during cooling.

Ar_4—the temperature at which delta ferrite transforms to austenite during cooling.

M_s—the temperature at which transformation of austenite to martensite starts during cooling.

M_f—the temperature, during cooling, at which transformation of austenite to martensite is substantially completed.

NOTE—All these changes except the formation of martensite occur at lower temperatures during cooling than during heating, and depend on the rate of change of temperature.

Figure 11.2 (*Continued*)

The critical temperature points for hardening steel are also called the *decalescence* and *recalescence points.* These critical temperature points have a direct relation to the hardening of steel. Unless the hardening temperature passes the decalescence point, no hardening can take place, and unless the steel is cooled suddenly before its temperature reaches the recalescence point, no hardening can take place. These critical temperature points (decalescence and recalescence) vary for different types of steels and must be determined by tests. This variation in critical temperature points makes it necessary to heat different steels to different hardening temperatures together with the proper quench, or cooling rate.

The maximum temperature to which a steel is heated before quenching to harden is called the *hardening temperature.* The hardening temperatures for steels of various carbon contents may be summarized generally by the following:

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Carbon content, %	Hardening temperature, °F
0.65–0.80	1450–1550
0.80–0.95	1410–1460
0.95–1.10	1390–1430
1.10 and over	1380–1420

Average hardening and tempering temperatures of steels. Generally, the average hardening temperature range for carbon and alloy steels is from 1375 to 1575°F. The average tempering range for steels is from 300 to 700°F.

11.4.1 Treatments for heat-treating grades of carbon steels

Figure 11.3 lists data for heat treating the common-usage heat-treating grades of carbon steels. The tempering temperatures are not shown, and tempering is not mandatory on many applications. When tempering is required, the tempering range varies from 250 to 450°F.

11.4.2 Heat treatments for directly hardenable grades of alloy steels

Figure 11.4 lists data for heat treating the common-usage directly hardenable grades of alloy steels. Tempering temperatures range from 250 to 350°F.

11.4.3 Heat treatment of tool steels

Tool steels are an important family of steels that have many applications throughout industry. The heat treatment and application of the different grades or classes of tool steels are covered in Sec. 8.2.2, "Heat Treatment of Tool Steels."

11.4.4 Quenching baths and temperatures

The purpose of a quenching bath is to cool the heated steel at a rate that is faster than the critical cooling rate. To obtain different cooling rates, different quenching baths are used, including

- Water bath (70 to l00°F bath temperature)
- Water spray (ambient temperature)

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SAE Steel	Normalizing Temperature (°F)	Annealing Temperature (°F)	Hardening Temperature (°F)	Quenching Medium
1025 1030	.....	.....	1575-1650	Water or brine
1035	.....	.....	1525-1575	oil or water
1036	1600-1700	.....	1525-1575	oil or water
1038 1039* 1040	1600-1700	.....	1525-1575	oil or water
1041	1600-1700 and/or	1400-1500	1474-1550	oil
1042 1043* 1045* 1046* 1050*	1600-1700	.....	1475-1550	oil or water,
1052 1055 1060 1065 1070 1074	1550-1650 and/or	1400-1500	1475-1550	oil
1078	.....	1400-1500	1450-1500	water or brine
1080 1090	1550-1650 and/or	1400-1500■	1450-1500	oil ♦
1095	....	1400-1500■ 1400-1500■	1450-1500 1500-1600	oil, water or brine oil
1137	1600-1700 and/or	1400-1500	1525-1575	oil or water
1140	1600-1700	.....	1500-1550	oil or water
1141 1144	1600-1700	1400-1500	1475-1550	oil
1146	1600-1700	.....	1475-1550	oil or water

NOTES: * = Commonly used on parts where induction hardening is employed. However, all steels from SAE 1030 up may have induction hardening applications. ♦ = May be water or brine quenched by special techniques such as partial immersion, or time-quenched; otherwise, they are subject to quench cracking. ■ = Spheroidal structures are often required on these high-carbon steels for machining purposes and should be cooled very slowly or be isothermally transformed to produce the desired structure.

Figure 11.3 Table of treatments for heat-treating grades of carbon steel.

- Brine solution (9% by weight or 0.75 lb sodium chloride per gallon of water)
- Caustic soda solution [5% solution by weight potassium hydroxide (lye)]
- Oil (ambient or 90 to 140°F)

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SAE Steel	Normalizing Temperature (°F)	Annealing Temperature (°F)	Hardening Temperature (°F)	Quenching Medium
1330	1600-1700 and/or	1500-1600	1525-1575	water or oil
1335 1340	1600-1700 and/or	1500-1600	1500-1550	oil
4037	.....	1525-1575	1500-1575	oil
4047	.....	1450-1550	1500-1575	oil
4130	1600-1700 and/or	1450-1550	1600-1650	water or oil
4137 4140 4145 4150	1600-1700 and/or	1450-1550	1550-1600	oil
4340	1600-1700 & temper	1100-1225	1475-1525	oil
5130 5132 5140 5150	1650-1750 and/or	1450-1550	1500-1550	water or caustic oil oil
50100 51100 52100	....	1350-1450	1425-1475 1500-1600	water oil
6150	1650-1750 and/or	1550-1650	1600-1650	oil
9260	.....	.....	1500-1650	oil
8630	1600-1700	1450-1550	1550-1650	water or oil
8637 8640	1600-1700 and/or	1450-1550	1525-1575	oil
8645 8650	1600-1700 and/or	1450-1550	1500-1550	oil

NOTE: Except as noted, the steel is to be tempered to the required hardness. The exceptions are gears made from steels 4037 and 5150; temper at 350 to 400°F.

Figure 11.4 Table of heat treatments for directly hardenable grades of alloy steels.

- Oil over water
- Molten salt bath (nitrate salts) to 700°F
- Forced air

11.5 Tempering and Case Hardening Steels

The purpose of tempering or drawing is to reduce the brittleness of hardened steel and to remove the internal stresses caused by the

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sudden cooling or quenching done in the hardening operation. In the tempering operation, the hardened steel is heated to a certain temperature and then quench cooled. Steel in the fully hardened condition consists mainly of martensite. When reheated to a temperature of approximately 300 to 750°F, a softer and tougher structure called *troostite* is formed. When the hardened steel is reheated to a temperature from 750 to 1290°F, a structure called *sorbite* is formed, which has less strength than troostite but is much more ductile.

11.5.1 Tempering temperatures for steels

The color of the oxide coating on the reheated steel was used in the past as a means of determining the tempering temperature. Since this color may be affected by the composition of the steel, it is not considered to be the most reliable method of determining the tempering temperature, although it served satisfactorily for many years. Today, the optical (infrared) pyrometer is used to determine the temperature to very accurate limits. Figure 11.5 shows the tempering temperatures of plain carbon steels as indicated by their surface colors.

Figure 11.6 shows the temperatures of metals by the color of the radiation or glow of the metal. Metals below 900°F do not produce a radiated color but only the color of the oxide coating, if present.

This color scale may be used in an emergency situation, where a fair indication of hardening temperature may be made for hardening

Degrees Fahrenheit	Degrees Celsius	Color of Steel
430	221.1	Very pale yellow
440	226.7	Light yellow
450	232.2	Pale straw-yellow
460	237.8	Straw-yellow
470	243.3	Deep straw-yellow
480	248.9	Dark-yellow
490	254.4	Yellow-brown
500	260.0	Brown-yellow
510	265.6	Spotted red-brown
520	271.1	Brown-purple
530	276.7	Light purple
540	282.2	Full purple
550	287.8	Dark purple
560	293.3	Full blue
570	298.9	Dark blue
640	337.8	Light blue

Figure 11.5 Tempering temperatures by color indication for plain carbon steels.

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Temperature (°F)	Temperature (°C)	Color
932 - 1,022	500 - 550	Dull red
1,202 - 1,382	650 - 750	Dark red
1,562 - 1,742	850 - 950	Bright red
1,922 - 2,102	1,050 - 1,150	Yellowish red
2,282 - 2,462	1,250 - 1,350	Dull white
2,642 - 2,822	1,450 - 1,550	Bright white

Figure 11.6 Color scale for metal temperatures based on radiated color (glow).

plain carbon steels, and Figure 11.5 surface color equivalent temperatures may be used for tempering.

Additional data on hardening and tempering steels may be obtained from Chap. 4, "Materials and Their Uses." A good understanding of the hardening and tempering operations used today may be obtained by reviewing the heat-treatment terms and definitions in Sec. 11.3.

11.5.2 Case hardening carbon and alloy steels

The case-hardening operation is performed on steels when a tough outer layer is required on the part and through-hardening of the steel is not required. This process has applications on parts that must be hardened to prevent wear on the outer surfaces only, whereas the core remains at its normal condition. Case hardening of low-carbon steels is a two-step operation. First, the outer layer of the part is carburized by introducing carbon into the surface, and second, the outer carburized layer is heat-treated to form a hard "case." Surface- or case-hardening processes include

- Carburization
- Cyanide hardening
- Nitriding
- Carbonitriding
- Induction hardening
- Flame hardening

Low-carbon steels containing 0.10 to 0.20 percent carbon are suitable for carburized case-hardening operations. Additional heat-treating data may be found in Chap. 4, "Materials and Their Uses."

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Hardening and Tempering Steels and Nonferrous Alloys

Case-hardening depths

Light case: 0.003 to 0.015 in

Medium case: 0.015 to 0.040 in

Heavy case: 0.040 to 0.250 in

Case depth measurements. A production method for determining the depth of the case-hardened layer consists of air cooling a test pin from the carburizing temperature, reheating to 1475°F, and quenching in oil. This treatment refines the effective case and leaves the core material coarse-grained. Etching the fractured surface of the test pin in an aqueous solution of 7% concentrated nitric acid produces good contrast between the case-hardened layer and the core material. The test pin is made of the same material as the case-hardened parts being checked and consists of a cylindrical pin 0.500 in in diameter, 3.5 in long, with a 0.468-in-diameter groove (0.060 in wide), approximately 0.30 in in from the end of the pin. Test rings usually are 1.500 in outside diameter with a 0.75-in hole through the center of the ring and a thickness of 0.375 in.

Other methods of determining the case depth include

- Reading of case depth with a Brinell microscope
- Step grinding and reading the Rockwell hardness at different depths
- Bluing of the fractured surface
- Carbon-cut analysis
- The martensite-start method

Cyanide case-hardening precautions. Cyanide compounds are deadly poisons. Care should be taken so that even minute portions are not consumed accidentally. In storage, keep cyanide-containing salts separate from acids because mixing these chemicals will produce deadly hydrocyanic gas. Do not add nitrate or nitrite salts to those containing cyanide because of the danger of explosion.

Surface hardness versus case depth. Figure 11.7 shows several different common steels and the case depth to be expected from the Brinell hardness reading taken on the surface of the case-hardened part.

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Case Depth as Determined by Brinell Hardness - Tabulated values are in inches and indicate case depths.

Steel	SAE 1020		SAE 6118		SAE 1020		SAE 4617		SAE 8620		SAE 4820	
Quench Temp (°F)	1675	1500	1675	1500	1675	1500	1675	1500	1675	1500	1675	1500
Quench Medium	Oil	Oil	Oil	Oil	Water	Water	Oil	Oil	Oil	Oil	Oil	Oil
Brinell												
156	.....	0.000										
167	.....	0.010										
170	.....	0.014										
179	0.000	0.019										
187	0.007	0.024										
192	0.009	0.026	.....	.....	.....	0.000						
197	0.011	0.029	.....	.....	.....	0.003						
207	0.016	0.035	.....	.....	.....	0.005						
217	0.023	0.041	.....	.....	.....	0.009	.....	0.000				
229	0.030	0.049	.....	.....	0.000	0.013	.....	0.004				
241	0.035	0.069	.....	0.000	0.005	0.018	.....	0.009				
255	0.040	0.077	.....	0.003	0.008	0.023	.....	0.015				
269	0.046	.....	.....	0.007	0.015	0.027	0.000	0.021				
285	0.053	.....	.....	0.013	0.022	0.034	0.007	0.024	.....	0.000		
302	0.060	.....	.....	0.018	0.027	0.039	0.010	0.028	.....	0.005		
321	0.074	.....	0.000	0.023	0.034	0.046	0.013	0.032	0.000	0.009		
341	.....	.....	0.004	0.029	0.041	0.054	0.017	0.035	0.003	0.012	.....	0.000
363	.....	.....	0.009	0.036	0.048	0.062	0.021	0.039	0.005	0.016	0.000	0.004
387	.....	.....	0.014	0.043	0.056	.....	0.024	0.041	0.010	0.022	0.008	0.010
412	.....	.....	0.019	0.048	0.062	.....	0.030	0.045	0.016	0.027	0.012	0.015
444	.....	.....	0.026	0.060	.....	.....	0.033	0.048	0.022	0.035	0.024	0.022
460	.....	.....	0.030	.....	.....	.....	0.035	0.051	0.026	0.039	0.028	0.026
477	.....	.....	0.034	.....	.....	.....	0.037	0.054	0.030	0.043	0.033	0.030
495	.....	.....	0.038	.....	.....	.....	0.039	0.056	0.034	0.047	0.038	0.035
512	.....	.....	0.042	.....	.....	.....	0.043	0.058	0.037	0.050	0.043	0.039
532	.....	.....	0.046	.....	.....	.....	0.051	0.060	0.042	0.055	0.049	0.043
555	.....	.....	0.051	.....	.....	.....	0.064	.....	0.047	0.061	0.055	0.049
578	.....	.....	0.057	.....	.....	.....	.....	.....	0.051	0.066	0.063	0.054
600	.....	.....	0.062	.....	.....	.....	.....	.....	0.055	.....	.....	0.060
627	.....	.....	.....	.....	.....	.....	.....	.....	0.061	.....	.....	.....

Figure 11.7 Case-depth table.

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Hardening and Tempering Steels and Nonferrous Alloys

11.5.3 Heat treatments for carburizing grades of carbon steels

Figure 11.8 shows the heat-treating process for carburizing grades of some of the common carbon steels.

11.5.4 Heat treatments for carburizing grades of alloy steels

Figure 11.9 shows the heat-treating process for some of the common carburizing grades of alloy steels.

Note: Extensive data on hardening all types of steels are contained in Chap. 4, "Materials and Their Uses." Also, in Sec. 8.2.2, "Heat Treatment of Tool Steels," data are shown for hardening these classes of steels.

11.6 Heat Treatment of Aluminum Alloys

The heat treatment of aluminum alloys is a precision operation. The temperature/time cycles are critical and must be carried out by using the proper equipment and controls. The general types of heat treatments applied to aluminum and its alloys are

1. Preheating or homogenizing to reduce chemical segregation of cast structures and to improve their workability
2. Annealing to soften strain-hardened (work-hardened) and heat-treated alloy structures to relieve stresses and to stabilize properties and dimensions
3. Solution heat treatments to effect solid solution of alloying constituents and improve mechanical properties
4. Precipitation heat treatments to provide hardening by precipitation of constituents from solid solution

11.6.1 Solution heat treatment of aluminum alloys

The solution heat treatment of aluminum alloys improves mechanical properties by developing the maximum practical concentration of the hardening constituents in solid solution. This requires heating the aluminum alloy part to a temperature close to the eutectic temperature, holding it there long enough to effect the desired solution, and then quenching fast enough to retain the desired solid solution.

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SAE Steel	Normalizing Temperature (°F)	Carburizing Temperature (°F)	Cooling Method	Reheat Temp. (°F)	Cooling Medium	Second Reheat (°F)	Cooling medium	Temper (°F)
1010	....	1650-1700	water/brine	....	....	....	....	250-400
1015	....	1650-1700	oil or water	1400-1450	water/brine	....	....	250-400
1018	....	1650-1700	cool slowly	1650-1700	oil/water	1400-1450	water/brine	250-400
1020	....	1500-1650	air/oil	....	....	....	....	optional
1024	1650-1750	1650-1700	oil	....	....	....	....	250-400
1025	....	1650-1700	water/brine	....	....	....	....	250-400
1026	....	1500-1650	oil/water	....	....	....	....	optional
1027	....	1350-1575	air/oil	....	....	....	....	optional
1030	....	1500-1650	oil/water	....	....	....	....	optional
1117	....	1650-1700	cool slowly	1650-1700	oil/water	1400-1450	water/brine	250-400
1118	....	1500-1650	oil/water	....	....	....	....	optional

NOTE: Even when the tempering temperatures are shown, the tempering operation is not mandatory on many applications. Tempering is generally employed for a partial stress relief and improves resistance to cracking from grinding operations. Higher temperatures than those shown may be used where the hardness specification on the finished parts permits.

Figure 11.8 Heat-treatment table for carburizing grades of common carbon steels.

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SAE Steel	Alternate Pretreatments Normalize■	+ Temper♦	Cycle Anneal	Carburizing Temperature (°F)	Cooling Method	Reheat Temp (°F)	Cooling Medium	Tempering Temp (°F)●
4023	Yes	.....	Yes	1650-1700	oil quench	.....	.....	250-350
4027								
4028								
4118	Yes	.....	.....	1650-1700	oil quench	.....	.....	250-350
4320	Yes	.....	Yes	1650-1700	oil quench	1425-1475	oil	250-350
4620				1650-1700	cool slowly	1475-1525	oil	250-350
4820	.....	.....	.....	1650-1700	oil quench	.....	.....	250-350
5120	Yes	.....	.....	1650-1700	cool slowly	1500-1550	oil	250-350
8615	Yes	.....	Yes	1650-1700	oil quench	1475-1525	oil	250-350
8617						1525-1575		
8620					cool slowly	1475-1525		
8622					cool slowly	1525-1575		
8720				1500-1650	oil quench	.....	.....	

NOTE: ■ Normalizing temperatures should be not less than 50°F higher than the carburizing temperature, followed by air cooling. ♦ After normalizing, reheat to temperature of 1000 to 1250°F and hold for approximately 4 hours. ● The tempering treatment is optional.

Figure 11.9 Heat-treatment table for carburizing grades of common alloy steels.

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The usual quenching medium for aluminum alloys is water. In quenching some products, water below 100°F provides the required quench rate for optimal properties of the alloy being heat treated.

In other alloys or products, the water may be heated to temperatures above l00°F or even to the boiling point to control distortion and residual internal stresses. Hot oil is also used for some applications because it provides a quenching rate that improves resistance to stress corrosion. The water quench is either by total immersion or by spray.

The recommended conditions of temperature and time for heat treating some of the common aluminum alloys, produced by various methods, are given in Figs. 11.10 through 11.15.

Alloy Designation	Temper	Solution Heat Treatment Metal Temperature (°F)	Precipitation Heat Treatment Metal Temp. (°F)	Time @ Temp. Hours
2014	T4, T6, T651	935	320	18
2024	T3, T4, T6	920	375	16
6061	T4, T6	985	320	18
7075	T6, T651	900	250	24
7178	T6, T651	875	250	24

Figure 11.10 Heat-treatment table for aluminum alloy sheet and plate.

Alloy Designation	Temper	Solution Heat Treatment Metal Temperature (°F)	Precipitation Heat Treatment Metal Temp. (°F)	Time @ Temp. Hours
2014	T4, T6, T651	935	320	18
2024	T351	920	.....	.....
6061	T4, T6, T651	980	350	8
7075	T6, T651	870	250	24
7178	T6, T651	870	250	24

Figure 11.11 Heat-treatment table for extruded aluminum alloy rod, bar, shapes, and tube.

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Alloy Designation	Temper	Solution Heat Treatment Metal Temperature (°F)	Precipitation Heat Treatment Metal Temp. (°F)	Time @ Temp. Hours
2011	T3	975	.....	.....
2014	T4, T6, T651	935	320	18
2024	T3, T4,	920	.....	.....
	T6	920	375	16
6061	T4,	985	.....	.....
	T6, T651	985	320	18
7075	T6, T651	915	250	24
7178	T6, T651	900	250	24

Figure 11.12 Heat-treatment table for rolled or drawn aluminum alloy wire, rod, bar, shapes, and tube.

Alloy Designation	Temper	Solution Heat Treatment Metal Temperature (°F) (Quench water temp.)		Precipitation Heat Treatment Metal Temp. (°F)	Time @ Temp. Hours
2014	T4	935	(140-160)	.....	.....
	T6	935	(140-160)	340	10
2024	T4	920	(Room)	.....	.....
	T6	920	(Room)	375	18
6061	T6	985	(Room)	350	8
7075	T6	880	(140-160)	250	24
7178	T6	870	(Room)	250	24

Figure 11.13 Heat-treatment table for aluminum alloy forgings.

11.6.2 Precipitation heat treatment of aluminum alloys

The rate of precipitation from the supersaturated solid solution existing immediately after quenching increases as the temperature of the metal is raised above room temperature. Precipitation occurs naturally at room temperature, providing useful degrees of precipitation hardening for some alloys. Precipitation heat treatment generally denotes treatment at an elevated temperature and often

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Alloy Designation	Temper	Solution Heat Treatment Metal Temp. (°F)	Time Hours	Precipitation Heat Treatment Metal Temp. (°F)	Time Hours
142	T61	960	6	450	2
220	T4	810	16	.....	.....
319	T6	940	10	310	4
355	T6	980	10	310	4
356	T6	1000	10	310	4
357	T6	1000	10	350	6
363	T6	940	10	310	4
A750	T5	.....	.....	430	8

NOTE: Many of these alloys are covered by ASTM B26. Solution heat treatment is followed by quenching in water at 150 to 212°F. A boiling water quench is recommended when minimum quenching stresses and distortion are required. Maintain steady furnace temperatures for the solution heat treatment process.

Figure 11.14 Heat-treatment table for sand- and plaster-cast aluminum alloys.

Alloy Designation	Temper	Solution Heat Treatment Metal Temp. (°F)	Time Hours	Precipitation Heat Treatment Metal Temp. (°F)	Time Hours
142	T61	960	6	400	4
319	T6	940	6	310	4
354	T61	980	8	310	10
355	T6	980	6	310	4
356	T6	1000	8	310	4
357	T6	1000	8	350	6
359	T61	1000	10	310	10
750/A750	T5	.....	.....	430	8

NOTE: Many of these alloys are covered by ASTM B108. The solution heat treatment is followed by quenching in water at 150 to 212°F. Boiling water is recommended when minimum quenching stresses and distortion are required. Maintain steady furnace temperatures for the solution heat treatment process.

Figure 11.15 Heat-treatment table for permanent-mold cast aluminum alloys.

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Hardening and Tempering Steels and Nonferrous Alloys

is called *artificial aging.* See Figs. 11.10 through Figure 11.15 for the precipitation-hardening temperature/times for those alloys which may be precipitation hardened (artificially aged).

11.7 Heat Treating Beryllium-Copper Alloys

Beryllium-copper alloys are important metallic products that over recent years have found many applications in various industries, including the electrical, electronics, and mechanical industries. Beryllium-copper alloys have many desirable characteristics, including corrosion resistance, good electrical conductivity, good spring properties, good heat conductivity, and excellent stress fatigue resistance. Beryllium is also alloyed with nickel, called *beryllium-nickel alloys,* and their tensile strengths are quite high when the alloys are cold worked. Many products that formerly used spring-tempered phosphor-bronzes are now using the beryllium-copper alloys.

The element beryllium is toxic, as are its alloys. The Occupational Safety and Health Administration (OSHA) safety regulations prescribe the conditions under which these alloys should be processed. The percentage of the population to which beryllium causes toxicity is small, but safeguards must be taken. The toxic effects of beryllium are seen as chronic pulmonary (lung) problems.

In the heat treatment of beryllium-copper alloys, the product is furnace heated to a prescribed temperature and held at this temperature for a number of hours, followed by still-air cooling to room temperature. Figure 11.16 shows the popular and common beryllium-copper alloys and their heat-treatment procedures. Figure 11.17 defines the ASTM temper designations used in Fig. 11.16.

11.8 Cold Work Hardening of Metals and Alloys

Many metals and alloys obtain their physical properties through the process of work hardening. The work-hardening processes include drawing, rolling, stretching, and hammering. Materials such as phosphor-bronze acquire their spring characteristics through the action of cold rolling or drawing. The percentage of reduction of the cross-sectional area of the material determines the degree of "temper" in the material. Figure 11.17 lists the percentage of reduction that determines the temper designation for beryllium-copper

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Hardening and Tempering Steels and Nonferrous Alloys

Alloy Designation (UNS system)	Temper (*)	Heat Treatment Time/Temperature	Tensile Strength Kpsi
25	(TF00)	3 hrs @ 600 °F	140-175
(C17200)	(TH01)	2 hrs @ 600 °F	150-185
	(TH02)	2 hrs @ 600 °F	185-215
	(TH04)	2 hrs @ 600 °F	190-220
190	(TM00)	Mill	100-110
(C17200)	(TM01)	Mill	110-120
	(TM02)	Mill	120-135
	(TM04)	Mill	135-150
	(TM05)	Mill	150-160
	(TM06)	Mill	155-175
	(TM08)	Mill	175-190
290	(TM00)	Mill	100 minimum
(C17200)	(TM02)	Mill	120 minimum
	(TM04)	Mill	140 minimum
	(TM06)	Mill	155 minimum
	(TM08)	Mill	175 minimum
165	(TF00)	3 hrs @ 600 °F	150-180
(C17000)	(TH01)	2 hrs @ 600 °F	160-190
	(TH02)	2 hrs @ 600 °F	170-200
	(Th04)	2 hrs @ 600 °F	180-210
	(TM00)	Mill	100-110
	(TM01)	Mill	110-120
	(TM02)	Mill	120-135
	(TM04)	Mill	135-150
	(TM05)	Mill	150-160
	(TM06)	Mill	155-175
3 (C17510) and 10 (C17500)	(TF00)	2-3 hrs @ 900 °F	100-130
	(TH04)	2-3 hrs @ 900 °F	110-135
174 (C17410)	(TH04)	Mill	110-130

NOTE: (*) = ASTM alphanumeric code for product tempers. Mill = product normally heat treated at the mill. For heat treatment, the part must be fully annealed, then accurately held at the indicated temperatures for the times shown. Uniform heating of the parts within the furnace MUST be maintained for a successful heat treatment. Annealed strip which is "dead-soft" offers maximum deep drawing and die-forming capabilities.

Figure 11.16 Heat-treatment table for beryllium-copper alloys.

alloys. The phosphor-bronze alloys also receive their temper designations from the percentage of reduction that takes place in the cold-rolling operation (quarter hard, half hard, full hard, spring, and extra spring).

Stainless steels such as AISI types 303, 304, and others may acquire very high tensile strengths and spring properties through the cold-rolling process. The 300 series stainless steels are termed

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Hardening and Tempering Steels and Nonferrous Alloys

ASTM Designation	Description	Cold Rolled Thickness Reduction in Percent
TB00	Solution annealed	0
TD01	Quarter hard	11
TD02	Half-hard	21
TD03	Three-quarters hard	29
TD04	Hard	37
TF00	The suffix "T" added to temper designations indicates that the material has been age-hardened by the standard heat treatment.	
TH01		
TH02		
TH03		
TH04		
TM00	Mill hardened to specific property ranges, no further heat treatment required.	
TM01		
TM02		
TM04		
TM05		
TM06		
TM08		

NOTE: Temper designations are defined in the specification ASTM B601, "Standard practice for temper designations for copper and copper alloys".

Figure 11.17 ASTM temper designations (for Fig. 11.16).

austenitic and cannot be heat treated by using conventional heat-treating processes. The spring properties of these and many other metals and alloys are obtainable only through cold-working processes. The martensitic stainless steels (400 series) may be heat treated using conventional heat-treating methods. The 440 series stainless steels are popular martensitic stainless steels that may be hardened to a high degree by heating and quenching at specified temperatures and cooling rates (see Chap. 4, "Materials and Their Uses," for hardening procedures for all classes of steels).

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Chapter

12

Castings, Moldings, Extrusions, and Powder-Metal Technology

12.1 Castings

The casting of metals and alloys is an important branch of the metalworking industry. Castings allow parts to be made at a rapid pace with controlled accuracy. Castings replace parts that otherwise would be difficult or impossible to machine and very costly to manufacture. However, castings cannot replace many types of machined parts because of material, configuration, and other physical considerations. Many types of processes are used in the casting and foundry industries to produce cast parts in different materials and for various dimensional accuracy requirements. The casting processes or methods that are in use today include

- Sand casting
- Shell casting
- Carbon dioxide casting
- Fluid sand casting
- Composite-mold casting
- Plaster-mold casting
- Slush casting

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- Evaporative pattern casting (EPC)
- Die casting
- Permanent-mold casting
- Ceramic-mold casting
- Investment casting (lost-wax process)

The casting method or process chosen by the design engineer and the foundry is determined by the following factors:

- Type of metal to be cast
- Size of part to be cast
- Required cast accuracy of the part
- Economics
- Required secondary operations such as machining, hardening, welding, and plating

12.1.1 Sand casting

In the sand-casting process, a wooden, plastic, or metal pattern is packed in a special sand, which is dampened with water and then removed, leaving a hollow space having the part's shape. The pattern is purposely made larger than the size of the cast part to allow for shrinkage of the casting as it cools.

The mold consists of two steel frames, which are called the *cope* (top half) and the *drag* (bottom half). Figure 12.1 is an illustration of a typical sand-casting setup.

Sand cores may be placed in the cavity to produce holes in the part where required. Once the cope and drag are clamped together, the molten metal is poured into the *gate* of the mold. Vent holes placed appropriately in the mold allow hot gases to escape from the mold cavity during pouring. The pouring temperature of the metal is always made a few hundred degrees higher than the melting point so that the metal has good fluidity during the pour and does not cool prematurely, causing voids in the part.

Sand casting is the least expensive of all the casting processes on a part-to-part basis, but a need for secondary machining operations may indicate the use of one of the other casting processes. Figure 12.2 shows a sand-cast part made of a copper alloy. This part would be difficult to machine from solid stock.

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Castings, Moldings, Extrusions, and Powder-Metal Technology

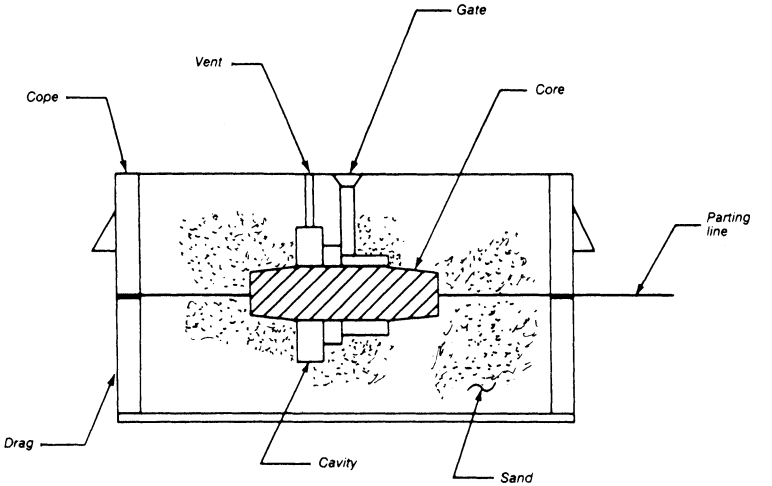

Figure 12.1 A typical sand-casting setup.

Figure 12.2 A typical sand-cast copper alloy part prior to machining.

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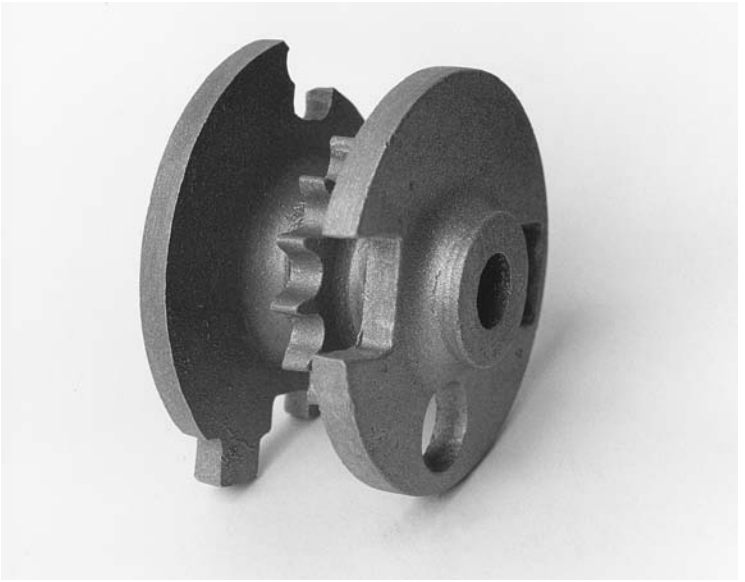

Figure 12.3 An intricate sand-cast aluminum alloy part.

Figure 12.3 shows another sand-cast part of intricate design. This part is made of 356-T6 aluminum alloy (heat treated). Note that at the center section of the part there is a sprocket for number 40 American National Standards Institute (ANSI) roller chain. The sprocket in this application does not need a high degree of accuracy because the sprocket and chain action is only intermittent. A part of such design would be extremely difficult and costly to manufacture using the machining processes or methods.

Figure 12.4 shows some of the gating and venting methods employed in sand casting and similar casting processes. Figure 12.5 shows a typical combination casting-machining engineering drawing. This drawing provides enough information for the pattern maker, foundry, and machine shop to be able to produce the part.

12.1.2 Shell casting

This process entails forming a mold from a mixture of sand and a thermosetting-resin binder. The sand and thermoset mix are placed against a heated pattern, which causes the resin to bind the sand particles and form a strong shell. After the shell is cured and stripped

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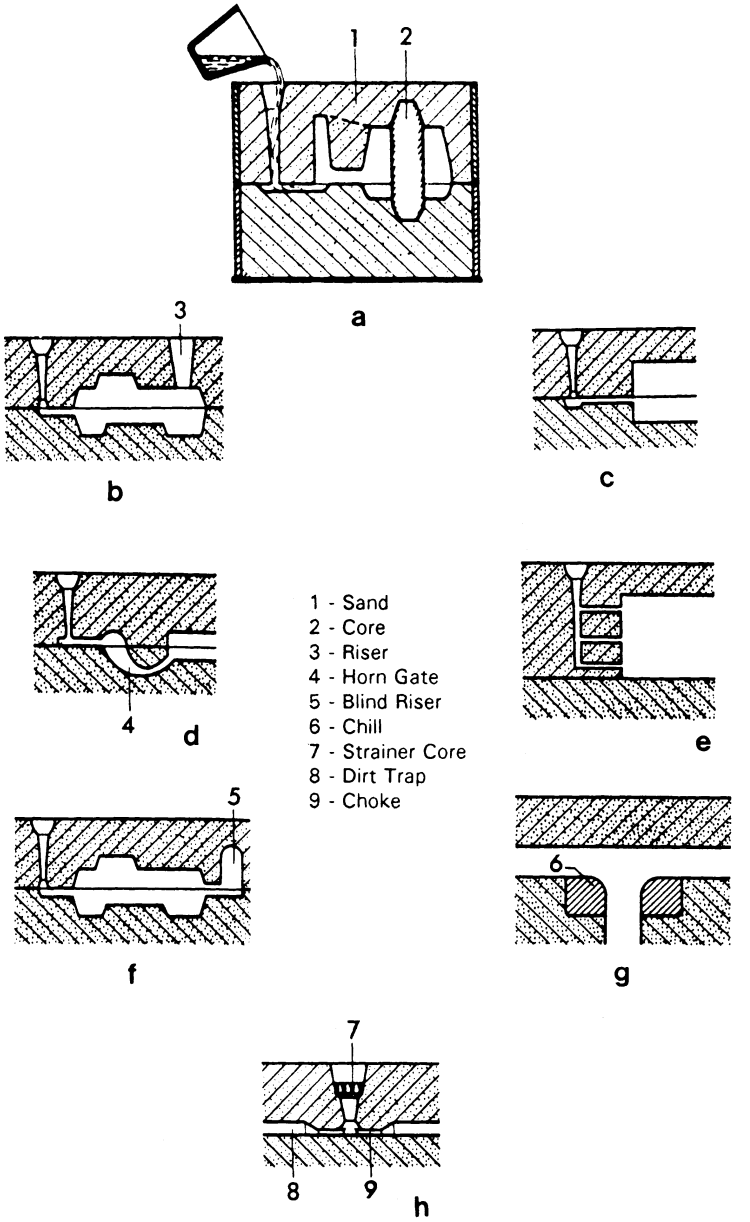

Figure 12.4 Gating, venting, and chills.

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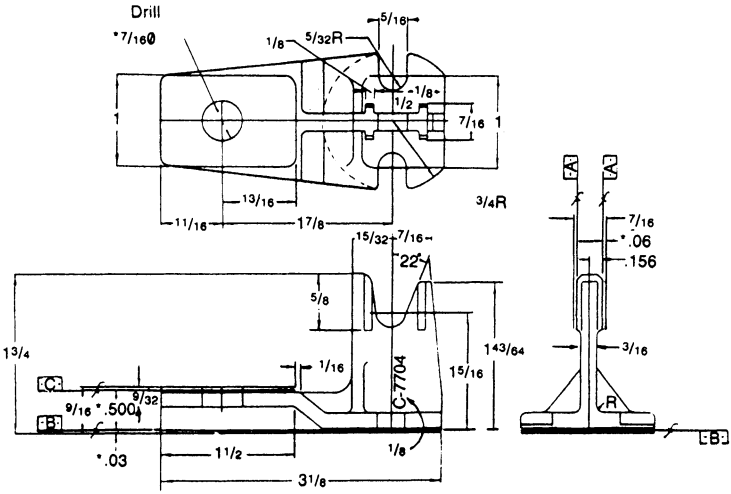

NOTES:
1- All dimensions in fractions for pattern. Tolerance = ± 1/64. (Use minimum draft angles)
2- -Indicates machined surface.
*-Indicates machining dimensions ± .005″
3- Surfaces -A- to be machined parallel to one another and perpendicular to surface -B-. Surface -C- to be parallel to surface -B-. Tolerance .003 total misalignment.
4- Δ material = CDA * 811000, 99.7& copper, 92% IACS conductivity.
5- Grind all flash lines and sharp edges from casting.
6- Fillet radii = 1/16″.
7- All machined surfaces to be 63 RMS maximum.
8- Add part number on the casting as indicated.
Δ- Alternate material = chrome copper, CDA * 81500 sand cast Mil Spec MIL-C-19310, heat treated, conductivity = 82% IACS.

Casting & Machining Drawing Sample

Figure 12.5 Typical casting-machining drawing.

from the pattern, cores may be set. The cope and drag are secured together and placed in a flask with added backup material. The mold is then ready for pouring the molten metal.

12.1.3 Carbon dioxide casting

The carbon dioxide process uses sodium silicate (water glass) binders instead of the clay binders employed in conventional sand casting. Treated with carbon dioxide gas, the sodium silicate–sand mixture is dried and strengthened.

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Ready-for-use cores or molds can be made using this process in a few minutes with no baking required. Excellent dimensional accuracy is obtained, even while making cores rapidly. This process is used more often to make cores than to make molds.

12.1.4 Plaster-mold casting

This process is used when nonferrous metals must be cast more accurately than is possible with conventional sand casting. The four recognized plaster-mold processes are

- Conventional mold
- Match-plate pattern
- The Antioch method
- The foamed plaster method

Castings produced by the plaster-mold process have smoother surfaces, better accuracy, and finer detail than those made by conventional sand casting, but they are also more expensive.

12.1.5 Composite-mold casting

Composite-mold casting uses different sections of the mold and cores made by different methods so that the greatest advantage is obtained from each process in the appropriate section. This process is usually chosen for aluminum parts and is sometimes called *premium-quality casting* or *engineered casting*. The use of plaster mold sections affords accuracy and stability wherever they are essential on the cast part. Composite molds are used for the following reasons:

- Decreased cost of mold material
- Increased casting accuracy
- Decreased amount of gassing
- Improved finish or surface
- Quicker processing time

12.1.6 Investment casting

In this casting process, an expendable pattern is coated with a refractory slurry that sets at ambient temperature. The expendable

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pattern (wax or plastic) is then melted out of the refractory shell. Ceramic cores are used as required.

Two distinct processes or methods are followed in investment casting: shell investment and solid investment. Investment casting is also known as the *lost-wax process* and *precision casting*. Cast parts can be produced in almost any pourable metal or alloy. The finished parts are dimensionally accurate and generally are used "as cast." The process is used for high-accuracy, mass-produced parts and for jewelry making.

The economics of this process must be weighed against the complexity of the part. Simple parts generally are not economical to produce with this process. The process is advantageous for applicable parts not in excess of 10 lb weight, although heavier parts frequently are investment cast.

12.1.7 Ceramic-mold casting

Ceramic-mold techniques are proprietary processes. They use permanent patterns and fine-grain zircon and calcined, high-alumina mullite slurries for molding.

As in other processes, the molds are constructed as a cope and a drag. Fine detail may be produced with high dimensional accuracy. The refractory mold allows the pouring of high-melting-point metals and alloys. The ferrous alloys and metals are cast more commonly with this process. Aluminum, beryllium-copper, titanium, ductile iron, carbon and low-alloy steels, and tool steels are cast using ceramic-mold processes.

Two of the proprietary processes for ceramic-mold casting are

- The Shaw method
- The unicast method

12.1.8 Permanent-mold casting

In this process, a metal mold consisting of two or more parts produces the cast parts. Metal, sand, or plaster cores are also used, in which case the process is known as *semi-permanent-mold casting*.

Intricate castings can be produced, but mold cost is high. Not all metals and alloys can be cast, and some shapes cannot be made because of the parting line or the difficulty of removing the part from the mold. Suitable casting metals include

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- Aluminum alloys, up to 30 lb
- Magnesium alloys, up to 15 lb
- Copper alloys, up to 20 lb
- Zinc alloys, up to 20 lb
- Gray iron (hypereutectic), up to 30 lb

A variation of this process chills the cast metal rapidly, producing enhanced properties with regard to grain configuration and size. Surface qualities of permanent-mold castings are better than conventional sand castings, but the mold cost always must be evaluated with respect to quantity of parts produced and secondary operations required (machining) to produce a finished part. Many parts cast with this process can be used "as cast" when close tolerances are not required. Figure 12.6 shows a relatively complex part that was cast by the permanent-mold chill-cast process in an aluminum-bronze high-strength alloy.

The types of metals that can be permanent-mold cast are limited to those whose melting points are not above the copper-base alloys. Pouring higher-temperature alloys causes permanent damage to the steel molds.

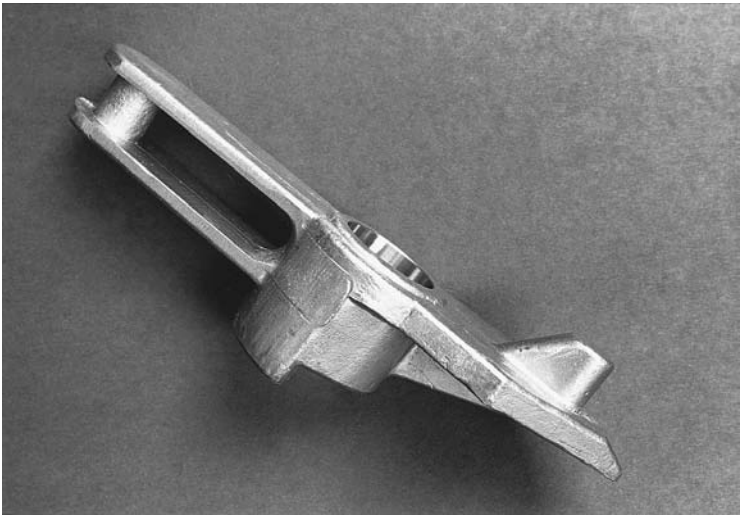

Figure 12.6 A permanent-mold chill-cast copper alloy part.

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12.1.9 Die casting

Die castings are made by forcing molten metal under high pressure into permanent molds called *dies.* The advantages of die casting include

- Complex shapes possible
- Thin-walled sections possible
- High production rates
- High dimensional accuracy
- High volume of parts with little change in the dies
- Minimum surface preparation required for plating

The disadvantages of die casting include

- Casting size limited: 50 lb seldom exceeded
- Air entrapment and porosity difficulties in complex shapes
- Expensive machinery and dies
- Limited to metals having melting points no higher than copper-base alloys

Figure 12.7 shows some typical die-cast parts made of zinc alloy. The intricate designs shown are produced easily with the die-casting process.

12.1.10 Evaporative pattern casting (EPC)

Although this process was known and patents were issued as early as 1958, it has not developed until very recently. In this process, a plastic expendable pattern (usually styrofoam) is coated with a refractory slurry and cured. The composition of the coating is critical to the casting process because it must allow outgassing of the vaporized styrofoam during pouring of the molten metal. When the molten metal pours into the mold, the styrofoam vaporizes and gases out of the mold and through the sand, leaving the molten metal in the void left by the styrofoam. The process allows the coated styrofoam pattern to be packed in sand as in conventional sand casting, except that a cope and drag are not needed because the pattern is not removed mechanically but vaporizes.

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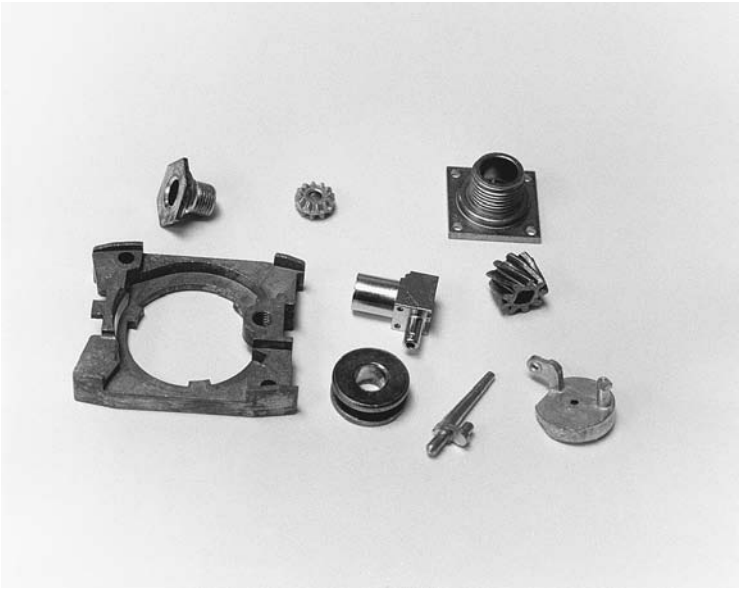

Figure 12.7 Typical die-cast zinc alloy parts.

This process permits the casting of any pourable metal or alloy. Complexity of parts is generally not a problem, and cores may be used as in the investment process. Complex shapes are devised by gluing sections of the styrofoam patterns together. Risers and gates form part of the pattern. The entire refractory-coated assembly is packed in sand and then cast. This process is highly applicable to some of the automated systems and robotization.

12.1.11 Slush casting

This process is limited to hollow castings. Zinc- or lead-base alloys generally are used. Products made by this process include lamp bases and parts and consumer novelty items.

In this process, the molten metal is poured into a split bronze mold and allowed to set a specified time, after which the mold is inverted, and the remaining liquid metal is poured out. Remaining is a thin shell that has hardened at the mold surface, thus producing a hollow cast shape.

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12.2 Ferrous Metal Alloys Used in Casting

The general ferrous metals and alloys used to produce castings include white iron, gray iron, malleable iron (ferritic and pearlitic), carbon steels, alloy steels, and stainless steels.

12.2.1 Gray iron castings

Carbon content in this iron ranges from 2.8 to 4 percent. Gray iron is poured at the lowest casting temperature and has the best castability and least shrinkage of all the ferrous metal cast alloys.

Gray iron may be heat treated in softening for better machinability or hardening for wear resistance. Pouring temperatures range from 2500 to 2700°F. Gray iron castings may be repaired by welding (shielded metal arc or oxyacetylene gas).

12.2.2 Ductile iron castings

The composition and handling of ductile irons are very similar to those of gray irons. The difference between the two irons is that in ductile iron, solidified graphite is spherical, whereas it is in flake form in gray iron. The metallurgy of the two irons is similar. Pouring temperatures range from 2500 to 2700°F. Ductile iron, as the name implies, has high ductility with resulting high impact strength for shock-load applications.

12.2.3 Malleable iron castings

This iron is produced from base metal having the following general composition:

Carbon: 2 to 3 percent

Silicon: 1 to 1.8 percent

Manganese: 0.2 to 0.5 percent

There are traces of sulfur, phosphorus, boron, and aluminum, with the remainder being iron.

The pouring range is 2700 to 2900°F. Ferritic malleable iron and pearlitic malleable iron receive different heat treatments to induce their metallurgic differences. Ferritic malleable iron must have a carbon-free matrix, and pearlitic malleable iron must have a matrix containing a controlled amount of carbon in the combined form.

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Liquid-quenched and tempered malleable iron is made by two processes, both of which produce high-quality, high-strength cast irons.

Note that white cast iron is frequently formed on purpose at high wear points of a casting by incorporating *chills* in the mold. A chill is an insert that causes rapid cooling of the cast iron, with the consequent formation of white iron at the points selected. White cast iron is brittle but extremely hard and wear resistant. Figure 12.4*g* shows the position of chills in a sand casting mold (6).

12.2.4 Steel and alloy-steel castings

Green sand, dry sand, shell, investment, and ceramic molds are all used to produce steel and alloy-steel castings. Plaster molds cannot be used because the high pouring temperature of steels destroys plaster molds. Green sand is the most widely used method for producing steel castings. Pouring temperature of steels for casting commonly reaches as high as 3200°F.

Large steel castings are commonly produced in dry sand molds and may range from 1 ton to over 100 tons in weight. Steel castings are welded for repairs and for joining two or more castings into a structural assembly.

12.3 Representative Casting Metals and Alloys

Shown in the following figures is a selection of data on commonly used engineering alloys for casting processes. These represent only a small sample of the materials that are available but include many favorite engineering alloys that have been proven by many design applications. Chapter 4, "Materials and Their Uses," also should be consulted for many other metallic alloys used throughout industry for a broad range of applications.

Representative casting metals and alloys. Figure 12.8 shows the physical properties of the common cast irons. Figure 12.9 shows the mechanical properties of cast structural steels. Figure 12.10 shows the designations and properties of cast stainless steels. Figure 12.11 shows the designations, types of processes, and physical properties of common cast aluminum alloys. Figure 12.12 shows the designations and mechanical properties of cast magnesium alloys. Figure 12.13 shows the Copper Development Association (CDA) designations and properties and application data for the common cast copper alloys.

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	Tensile Strength psi	Yield Strength psi	Elongation Elongation % in 2 in.	Impact Impact ft-lbs	Young's Modulus psi
Ductile iron	90,000	60,000	15	2	22×10^6
ASTM A536-77Δ	150,000	125,000	40	10	25×10^6
Gray iron*	20,000	12,000	*	0.5	12×10^6
ASTM A48-76	65,000	40,000		1.0	20×10^6
Malleable iron	50,000	30,000	70	10	25×10^6
(ferritic)	55,000	35,000	90	18	
Malleable iron	60,000	40,000	20	1	26×10^6
(pearlitic)	100,000	90,000	35	10	28×10^6
White iron	20,000	—	3	—	—
	50,000		10		

*Gray iron is not generally used for impact applications.
ΔDuctile iron is also Austempered (ADI), which approximately doubles its strength.

Figure 12.8 Physical properties of cast irons.

Grade	Tensile Strength, psi	Yield Strength, psi	Elongation % in 2 in	Impact ft-lbs	Endurance Limit, psi
60,000	63,000	35,000	30	12	30,000
65,000	68,000	38,000	28	35	30,000
70,000	75,000	42,000	27	30	35,000

Modulus of elasticity, typical: 29×10^6 to 30×10^6.

Figure 12.9 Mechanical properties of cast steels.

12.4 ASTM Listed Cast Irons and Steels

The American Society for Testing and Materials (ASTM) cast irons and steels shown in the following subsection have physical and chemical characteristics that make them suitable for the types of applications and services listed below:

- High-temperature applications
- Low-temperature applications
- Impact resistance
- Structural applications
- Pressure-vessel service

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Designation †	Tensile Strength, psi	Yield Strength, psi	Elongation % in 2 in	Impact Charpy	Young's Modulus, psi
CA-15	115,000	100,000	30	35	29×10^6
CC-50 *(HC)	70,000 110,000	65,000	18	45	29×10^6
CE-30 *(HE)	87,000 92,000	63,000	18	10	25×10^6
CH-20 *(HH)	80,000 88,000	50,000	38	15	28×10^6
Typical physical properties of cast alloy steels					
Melting temperature	2,700° to 2,800°F				
Thermal conductivity (B.t.u-ft/hr-ft^2-°F)	18 to 27				
Density, lb/in^3	0.283 to 0.284				
Electrical resistivity (micro-ohm cm)	227				
ASTM and SAE specifications—cast alloy steels					
General mechanical	A27, A148				
Low temperature applications	A352, A757				
Weldability	A216				
Automotive applications	SAE J435				

*Heat-resistant grades. †ACI (Alloy Casting Institute) designations.

Figure 12.10 Properties of cast stainless steels.

- High ductility
- Corrosion resistance

12.4.1 ASTM specifications for selected cast irons and cast steels

ASTM A159-83 (R1988), *Standard Specification for Automotive Gray Iron Castings*. See Fig. 12.14 for mechanical properties. The grades of gray cast iron consist of the following:

G1800: ferritic-pearlitic

G2500: pearlitic-ferritic

G3000: pearlitic

G3500: pearlitic

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Alloy Designation	Type	Uses and Typical Strengths
UNS A02010 (ANSI 201.0)	S PM	Very high strength, high impact, High ductility, high cost US = 60 YS = 50 El = 5.0
UNS A02060 (ANSI 206.0)	S PM	High tensile and yield, structural parts, automotive and aerospace US = 40 YS = 24 El = 8.0
UNS A02080 (ANSI 208.0)	S PM	Manifolds, valve bodies, pressure-tightness applciations US = 20 YS = 12 El = 1.5
UNS A02220 (ANSI 222.0)	S PM	Pistons and air-cooled cylinder heads US = 39/40
UNS A03190 (ANSI 319.0)	S	Low cost, general purpose alloy US = 31 YS = 20 El = 1.5
UNS A03540 (ANSI 354.0)	PM	High strength premium alloy US = 48 YS = 37 El = 3.0
UNS A03560 (ANSI 356.0)	S PM	For intricate work, good strength and ductility US = 33 YS = 22 El = 3.0
UNS A03600 (ANSI 360.0)	D	Very good casting and strength US = 44 YS = 25 El = 2.5
UNS A13600 (ANSI A360)	D	Excellent casting, corrosion resistance, thin walls, intricate parts US = 46 YS = 24 El = 3.5
UNS A03840 (ANSI 384.0)	D	General purpose alloy, thin sect. US = 48 YS = 24 El = 2.5
UNS A03900 (ANSI 390.0)	D	High wear resistance, cylinder heads, pistons, engine crankcases US = 41 YS = 35 El = 1.0

In the preceding table: *US* = ultimate strength, *YS* = yield strength in kpsi, *El* = elongation, % in 2 in, *S* = sand casting alloy, *PM* = permanent mold casting alloy, *D* = die casting alloy.

Figure 12.11 Aluminum casting alloys.

G4000: pearlitic

Figure 12.15 lists the typical applications for the automotive gray cast irons.

ASTM A 148/A 148M-89a, *Standard Specification for Steel Castings, High Strength, for Structural Applications*. Figure 12.16 lists the tensile strength properties.

ASTM A 297/A 297M-89, *Standard Specification for Steel Castings, Iron-Chromium, Iron-Chromium-Nickel, Heat Resistant, for General Applications*. Figure 12.17 lists the physical properties.

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Designation	Temper	US	YS	Elongation % in 2 in
ΔM10100	F	20,000	—	—
(ASTM-AM 100A)	T4	34,000	—	6
SAE 502	T6	35,000	17,000	—
ΔM11630	F	26,000	11,000	4
(ASTM-AZ 63A)	T4	34,000	11,000	7
SAE 50	T6	34,000	16,000	3
*M11910	—	34,000	23,000	3
(ASTM-AZ 91A)				
SAE 501				
*M11912	—	34,000	23,000	3
(ASTM-AZ 91B)				
SAE 501A				
ΔM11920	F	23,000	11,000	—
(ASTM-AZ 92A)	T4	34,000	11,000	6
	T6	34,000	18,000	1
ΔM16630	T6	40,000	27,000	5
(ASTM-ZE 63A)				

*Automotive die-casting alloys
ΔSand castings alloys

Figure 12.12 Magnesium casting alloys.

ASTM A 352/A 352M-89, *Standard Specification for Steel Castings, Ferritic and Martensitic, for Pressure Containing Parts, Suitable for Low-Temperature Service*. Table 12.1 lists the chemical, tensile, and impact properties.

ASTM A 436-84, *Standard Specification for Austenitic Gray Iron Castings*. Figure 12.18 lists the chemical and mechanical requirements.

ASTM A 439-83, *Standard Specification for Austenitic Ductile Iron Castings*. Figure 12.19 lists the chemical and mechanical properties.

ASTM A 487/A 487M-89a, *Standard Specification for Steel Castings Suitable for Pressure Service*. Tables 12.2 and 12.3 list the heat-treatment and mechanical requirements.

ASTM A 743/743M-89, *Standard Specification for Castings, Iron-Chromium, Iron-Chromium-Nickel, Corrosion Resistant, for General Applications*. Tables 12.4 and 12.5 list the heat-treatment and mechanical requirements.

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Alloy No. C80100
Composition: 99.95% copper, 0.05 trace elements
Conductivity: 100% IACS
Tensile strength: 19,000 psi min. to 25,000 psi typical
Yield strength: 6,500 psi min. to 9,000 psi typical (0.2% offset)
Typical uses: Electrical and thermal conductors, corrosion resistance applications.
Similar alloys: C80300, C80500, C80700, C80900
All are difficult to cast, with low casting yields.

Alloy No. C81500 (chrome-copper)
Composition: 1% chromium, balance copper
Conductivity: 82% IACS
Tensile strength: 45,000 psi min. to 51,000 psi typical (heat treated)
Yield strength: 35,000 psi. to 40,000 psi typical (0.5% exten. under load)
Typical uses: Electrical and thermal conductors where high strength and hardness are required. A premium quality alloy.

Alloy No. C81700
Composition: 0.4% beryllium, 0.9 cobalt, 0.9 nickel, 1.0 silver
Conductivity: 48% IACS
Tensile strength: 85,000 psi min. to 92,000 psi typical
Yield strength: 62,000 psi min. to 68,000 psi typical (0.2% offset)
Typical uses: Electrical and thermal conductors where high strength and hardness are required.

Alloy No. C82400 (former name: 165C)
Composition: 1.7% beryllium, 0.25 cobalt, remainder copper
Conductivity: 25% IACS
Tensile strength: 145,000 psi min. to 150,000 psi typical (heat treated)
Yield strength: 135,000 psi min. to 140,000 psi typical (0.2% offset)
Typical uses: Molds, cams, bushings, gears, bearings
Similar alloys: C82800, C82700, C82600

Alloy No. C83600 (115, leaded red brass, composition bronze)
Composition: 85% copper, 5.0 lead, 5.0 tin, 5.0 zinc
Conductivity: 15% IACS
Tensile strength: 30,000 psi min. to 37,000 psi typical (as cast)
Yield strength: 14,000 psi min. to 17,000 psi typical (0.5% exten. under load)
Typical uses: Pipie fittings, pump castings, impellers, small gears
Similar alloys: C83800, C84200, C84400, C84500

Alloy No. C85200 (400, leaded yellow brass)
Composition: 72% copper, 3.0 lead, 1.0 tin, 24.0 zinc
Conductivity: 18% IACS
Tensile strength: 35,000 psi min. to 38,000 psi typical (as cast)
Yield strength: 12,000 psi min. to 13,000 psi typical (0.5% exten. under load)
Typical uses: Ferrules, valves, hardware, plumbing fittings
Similar alloys: C85300, C85400, C85500

Figure 12.13 CDA designations and properties of cast copper alloys.

Brinell hardness measurements for castings and other applications. Calculation of the Brinell hardness number (BHN) can be performed using the equation shown in Sec. 4.8 of this *Handbook*. Table 12.6 is a table of Brinell hardness numbers as determined by the diameter of the indentation of a 10-mm ball at applied loads of 500, 1500, and

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Alloy No. C86100 (high-strength yellow brass, 90 kpsi manganese bronze)
Composition: 5.0 aluminum, 67.0 copper, 3.0 iron, 4.0 manganese, 21.0 zinc
Conductivity: 7.5% IACS
Tensile strength: 90,000 psi min. to 95,000 psi typical
Yield strength: 45,000 psi min. to 50,000 psi typical (0.2% offset)
Typical uses: Marine castings, gears, bushings, bearings
Similar alloys: C86200, C86300, C86400, C86500

Alloy No. C87800 (die-cast silicon brass)
Composition: 82.0 copper, 4.0 silicon, 14.0 zinc
Conductivity: 6.7% IACS
Tensile strength: 85,000 psi typical
Yield strength: 50,000 psi typical (0.2% offset)
Typical uses: High-strength die castings, lever arms, brackets, hex nuts, clamps
Similar alloys: C87900

Alloy No. C94400 (phosphor bronze, 312)
Composition: 81.0 copper, 11.0 lead, .35 phosphorus, 8.0 tin
Conductivity: 10% IACS
Tensile strength: 32,000 psi typical
Yield strength: 16,000 psi typical (0.5% exten. under load)
Typical uses: Bushings, bearings, electrical items

Alloy No. C95400 (aluminum-bronze 9C, 415)
Composition: 11.0 aluminum, 85.0 copper, 4.0 iron
Conductivity: 13% IACS
Tensile strength: 75,000 psi min. to 85,000 psi typical
Yield strength: 30,000 psi min. to 35,000 psi typical (0.5% exten. under load)
Typical uses: Bearings, worms, gears, bushings, valve guides
Similar alloys: C95200, C95300, C95500

Alloy No. C95700 (manganese aluminum bronze)
Composition: 8.0 aluminum, 75.0 copper, 3.0 iron, 12.0 manganese, 2.0 nickel
Conductivity: 3.1% IACS
Tensile strength: 90,000 psi min. to 95,000 psi typical
Yield strength: 40,000 psi min. to 45,000 psi typical (0.5% exten. under load)
Typical uses: Impellers, propellers, safety tools, valves, pump castings

Note: The preceding alloy numbers refer to the UNS numbering system for copper cast alloys. For a complete listing of copper cast alloys, refer to the CDA handbook of cast copper alloys available from the Copper Development Association.

Figure 12.13 (*Continued*)

3000 kgf (kilogram-force). The table may be used for determining the hardness of most metals and alloys.

12.5 Plastic Moldings

There are two classifications of plastics and their moldings: thermoplastics and thermoset plastics. Thermoplastics are basically the same chemically after molding as they were in the raw form. This means that once molded, they may be reused, in most cases, by chopping the parts into small pieces and remelting. Thermoset

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Mechanical Properties for Design Purposes

Grade	Hardness Range[A]	Tensile Strength, min, psi (kgf/mm^2)	Transverse Strength, min, lb (kg)[B]	Deflection, min, in. (mm)[B]
G1800	HB 143-187 5.0–4.4 BID	18 000 (14)	1720 (780)	0.14 (3.6)
G2500	HB 170-229 4.6–4.0 BID	25 000 (17.5)	2000 (910)	0.17 (4.3)
G3000	HB 187-241 4.4–3.9 BID	30 000 (21)	2200 (1000)	0.20 (5.1)
G3500	HB 207-255 4.2–3.8 BID	35 000 (24.5)	2450 (1090)	0.24 (6.1)
G4000	HB 217-269 4.1–3.7 BID	40 000 (28)	2600 (1180)	0.27 (6.9)

[A] Brinell impression diameter (BID) is the diameter in millimetres of the impression of a 10-mm ball at 3000-kg load.
[B] See Method A 438 for information concerning the B transverse test bar and the transverse test.

Figure 12.14 Mechanical properties of gray-iron castings. *(Reprinted with permission from the Annual Book of ASTM Standards, copyright 1992, American Society for Testing and Materials.)*

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Grade	General Data
G1800	Miscellaneous soft iron castings (as cast or annealed) in which strength is not of primary consideration. Exhaust manifolds may be made of this grade of iron, alloyed or unalloyed. These may be annealed castings for exhaust manifolds in order to avoid growth and cracking due to heat.
G2500	Small cylinder blocks, cylinder heads, air cooled cylinders, pistons, clutch plates, oil pump bodies, transmission cases, gear boxes, clutch housings, and light-duty brake drums.
G3000	Automobile and diesel cylinder blocks, cylinder heads, flywheels, differential carries castings, pistons, medium-duty brake drums, and clutch plates.
G3500	Diesel engine blocks, truck and tractor cylinder blocks and heads, heavy flywheels, tractor transmission cases, and heavy gear boxes.
G4000	Diesel engine castings, liners, cylinders, and pistons.

Figure 12.15 Typical applications of gray iron for automotive castings. *(Reprinted with permission from the Annual Book of ASTM Standards, copyright 1992, American Society for Testing and Materials.)*

plastics, once molded, cannot be remolded or reprocessed because they have a one-way chemistry that alters their "as molded" characteristics from their raw constituents.

Types of thermoplastics include

- ABS (acrylonitrile-butadiene-styrene)
- Acetal (Delrin)
- Acrylic (Lucite, Plexiglas)
- Cellulosics (acetates)
- Fluoroplastics (PTFE, FEP, PFA, CTFE, ETFE, PVDF)
- Nylon
- Phenylene oxide
- Polycarbonate (Lexan)
- Polyester (Mylar)
- Polyethylene
- Polyimide
- Polyphenylene sulfide
- Polypropylene
- Polystyrene

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Tensile Requirements

Grade	Tensile strength min, ksi [MPa]	Yield point min, ksi [MPa]	Elongation in 2 in. or 50 mm, min, %[A]	Reduction of Area, min, %
80-40 [550-275]	80 [550]	40 [275]	18	30
80-50 [550-345]	80 [550]	50 [345]	22	35
90-60 [620-415]	90 [620]	60 [415]	20	40
105-85 [725-585]	105 [725]	85 [585]	17	35
115-95 [795-655]	115 [795]	95 [655]	14	30
130-115 [895-795]	130 [895]	115 [795]	11	25
135-125 [930-860]	135 [930]	125 [860]	9	22
150-135 [1035-930]	150 [1035]	135 [930]	7	18
160-145 [1105-1000]	160 [1105]	145 [1000]	6	12
165-150 [1140-1035]	165 [1140]	150 [1035]	5	20
165-150L [1140-1035L][B]	165 [1140]	150 [1035]	5	20
210-180 [1450-1240]	210 [1450]	180 [1240]	4	15
210-180L [1450-1240L][B]	210 [1450]	180 [1240]	4	15
260-210 [1795-1450]	260 [1795]	210 [1450]	3	6
260-210L [1795-1450L][B]	260 [1795]	210 [1450]	3	6

[A] When ICI test bars are used in tensile testing as provided for in this specification, the gage length to reduced section diameter ratio shall be 4 to 1.
[B] These grades must be charpy impact tested.

Figure 12.16 Tensile-strength properties of steel castings. *(Reprinted with permission from the Annual Book of ASTM Standards, copyright 1992, American Society for Testing and Materials.)*

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Tensile Requirements

Grade	Type	Tensile Strength, min		Yield Point, min		Elongation in 2 in. [50 mm], min, %[A]
		ksi	[MPa]	ksi	[MPa]	
HF	19 Chromium, 9 Nickel	70	485	35	240	25
HH	25 Chromium, 12 Nickel	75	515	35	240	10
HI	28 Chromium, 15 Nickel	70	485	35	240	10
HK	25 Chromium, 20 Nickel	65	450	35	240	10
HE	29 Chromium, 9 Nickel	85	585	40	275	9
HT	15 Chromium, 35 Nickel	65	450	...	...	4
HU	19 Chromium, 39 Nickel	65	450	...	...	4
HW	12 Chromium, 60 Nickel	60	415	...	...	...
HX	17 Chromium, 66 Nickel	60	415	...	...	...
HC	28 Chromium	55	380	...	...	...
HD	28 Chromium, 5 Nickel	75	515	35	240	8
HL	29 Chromium, 20 Nickel	65	450	35	240	10
HN	20 Chromium, 25 Nickel	63	435	...	...	8
HP	26 Chromium, 35 Nickel	62.5	430	34	235	4.5

[A] When ICI test bars are used in tensile testing as provided for in this specification, the gage length to reduced section diameter ratio shall be 4 to 1.

Figure 12.17 Tensile strengths for steel, iron-chromium-nickel, and heat-resisting castings. *(Reprinted with permission from the Annual Book of ASTM Standards, copyright 1992, American Society for Testing and Materials.)*

- Polysulfone
- Polyurethane
- Polyvinyl chloride

Types of thermoset plastics include

- Alkyd
- Allyl (diallyl phthalate)
- Amino (urea, melamine)
- Epoxy (including cycloaliphatic)
- Phenolic
- Polyester
- Polyurethane
- Silicone

Polyesters and polyurethanes include thermosets that are also thermoplastics. Thermoset grades usually are filled with reinforcing

(Text continued on page 793.)

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TABLE 12.1 Chemical, Tensile, and Impact Requirements

Grade	Carbon steel	Carbon steel	Carbon-manganese steel	Carbon-molybdenum steel	2½% nickel steel	Nickel-chromium-molybdenum steel	3½% nickel steel	4½% nickel steel	9% nickel steel	12½% chromium, nickel-molybdenum steel
Element, % (max, except where range is given)	LCA	LCB[a]	LCC	LC1	LC2	LC2-1	LC3	LC4	LC9	CA6NM
Carbon	0.25[a]	0.30	0.25[a]	0.25	0.25	0.22	0.15	0.15	0.13	0.06
Silicon	0.60	0.60	0.60	0.60	0.60	0.50	0.60	0.60	0.45	1.00
Manganese	0.70[a]	1.00	1.20[a]	0.50–0.80	0.50–0.80	0.55–0.75	0.50–0.80	0.50–0.80	0.90	1.00
Phosphorus	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Sulfur	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.045	0.03
Nickel	0.50[b]	0.50[b]	0.50[b]	—	2.00–3.00	2.50–3.50	3.00–4.00	4.00–5.00	8.50–10.0	3.5–4.5
Chromium	0.50[b]	0.50[b]	0.50[b]	—	—	1.35–1.85	—	—	0.50	11.5–14.0
Molybdenum	0.20[b]	0.20[b]	0.20[b]	0.45–0.65	—	0.30–0.60	—	—	0.20	0.4–1.0
Copper	0.30[b]	0.30[b]	0.30[b]	—	—	—	—	—	0.30	—
Vanadium	0.03[b]	0.03[b]	0.03[b]	—	—	—	—	—	0.03	—
Tensile Requirements:[c]										
Tensile strength, ksi (MPa)	60.0–85.0 (415–585)	65.0–90.0 (450–620)	70.0–95.0 (485–655)	65.0–90.0 (450–620)	70.0–95.0 (485–655)	105.0–130.0 (725–895)	70.0–95.0 (485–655)	70.0–95.0 (485–655)	85.0 (585)	110.0–135.0 (760–930)
Yield strength,[d] min, ksi (MPa)	30.0 (205)	35.0 (240)	40.0 (275)	35.0 (240)	40.0 (275)	80.0 (550)	40.0 (275)	40.0 (275)	75.0 (515)	80.0 (550)
Elongation in 2 in or 50 mm, min, %[e]	24	24	22	24	24	18	24	24	20	15
Reduction of area, min, %	35	35	35	35	35	30	35	35	30	35

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Impact requirements Charpy V-notch[c,f]										
Energy value, ft·lbf (J), min value for two specimens and min avg of three specimens	13 (18)	13 (18)	15 (20)	13 (18)	15 (20)	30 (41)	15 (20)	15 (20)	20 (27)	20 (27)
Energy value, ft·lbf (J), min for single specimen	10 (14)	10 (14)	12 (16)	10 (14)	12 (16)	25 (34)	12 (16)	12 (16)	15 (20)	15 (20)
Testing temperature, °F (°C)	–25 (–32)	–50 (–46)	–50 (–46)	–75 (–59)	–100 (–73)	–100 (–73)	–150 (–101)	–175 (–115)	–320 (–196)	–100 (–73)

[a] For each reduction of 0.01% below the specified maximum carbon content, an increase of 0.04% manganese above the specified maximum will be permitted up to a maximum of 1.10% for LCA, 1.28% for LCB, and 1.40% for LCC.

[b] Specified Residual Elements—The total content of these elements is 1.00% maximum.

[c] See 1.2.

[d] Determine by either 0.2% offset method or 0.5% extension-under-load method.

[e] When ICI test bars are used in tensile testing as provided for in Specification A 703/A 703M, the gauge length to reduced section diameter ratio shall be 4 to 1.

[f] See Appendix X1.

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Chemical Requirements

Element	Composition, %							
	Type 1	Type 1b	Type 2	Type 2b	Type 3	Type 4	Type 5	Type 6
Carbon, total, max	3.00	3.00	3.00	3.00	2.60	2.60	2.40	3.00
Silicon	1.00–2.80	1.00–2.80	1.00–2.80	1.00–2.80	1.00–2.00	5.00–6.00	1.00–2.00	1.50–2.50
Manganese	0.5–1.5	0.5–1.5	0.5–1.5	0.5–1.5	0.5–1.5	0.5–1.5	0.5–1.5	0.5–1.5
Nickel	13.50–17.50	13.50–17.50	18.00–22.00	18.00–22.00	28.00–32.00	29.00–32.00	34.00–36.00	18.00–22.00
Copper	5.50–7.50	5.50–7.50	0.50 max	0.50 max	0.50 max	0.50 max	0.50 max	3.50–5.50
Chromium	1.5–2.5	2.50–3.50	1.5–2.5	3.00–6.00[A]	2.50–3.50	4.50–5.50	0.10 max	1.00–2.00
Sulfur, max	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Molybdenum, max	...	...	...	...	...	...	...	1.00

[A] Where some machining is required, the 3.00–4.00 % chromium range is recommended.

Mechanical Requirements

	Type 1	Type 1b	Type 2	Type 2b	Type 3	Type 4	Type 5	Type 6
Tensile strength, min, ksi (MPa)	25 (172)	30 (207)	25 (172)	30 (207)	25 (172)	25 (172)	20 (138)	25 (172)
Brinell hardness (3000 kg)	131 183	149 212	118 174	171 248	118 159	149 212	99 124	124 174

Figure 12.18 Chemical and mechanical requirements for austenitic gray-iron castings. *(Reprinted with permission from the Annual Book of ASTM Standards, copyright 1992, American Society for Testing and Materials.)*

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Chemical Requirements

Element	Type								
	D-2[A]	D-2B	D-2C	D-3[A]	D-3A	D-4	D-5	D-5B	D-5S
	Composition, %								
Total carbon, max	3.00	3.00	2.90	2.60	2.60	2.60	2.40	2.40	2.30
Silicon	1.50–3.00	1.50–3.00	1.00–3.00	1.00–2.80	1.00–2.80	5.00–6.00	1.00–2.80	1.00–2.80	4.90–5.50
Manganese	0.70–1.25	0.70–1.25	1.80–2.40	1.00 max[B]	1.00 max[B]	1.00 max[B]	1.00 max[B]	1.00 max[B]	1.00 max
Phosphorus, max	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Nickel	18.00–22.00	18.00–22.00	21.00–24.00	28.00–32.00	28.00–32.00	28.00–32.00	34.00–36.00	34.00–36.00	34.00–37.00
Chromium	1.75–2.75	2.75–4.00	0.50 max[B]	2.50–3.50	1.00–1.50	4.50–5.50	0.10 max	2.00–3.00	1.75–2.25

[A] Additions of 0.7 to 1.0 % of molybdenum will increase the mechanical properties above 800°F (425°C).
[B] Not intentionally added.

Mechanical Requirements

Element	Type								
	D-2	D-2B	D-2C	D-3	D-3A	D-4	D-5	D-5B	D-5S
	Properties								
Tensile strength, min, ksi (MPa)	58 (400)	58 (400)	58 (400)	55 (379)	55 (379)	60 (414)	55 (379)	55 (379)	65 (449)
Yield strength (0.2 percent offset), min, ksi (MPa)	30 (207)	30 (207)	28 (193)	30 (207)	30 (207)	. . .	30 (207)	30 (207)	30 (207)
Elongation in 2 in. or 50 mm, min, %	8.0	7.0	20.0	6.0	10.0	. . .	20.0	6.0	10
Brinell hardness (3000 kg)	139–202	148–211	121–171	139–202	131–193	202–273	131–185	139–193	131–193

Figure 12.19 Specifications for austenitic ductile iron castings. *(Reprinted with permission from the Annual Book of ASTM Standards, copyright 1992, American Society for Testing and Materials.)*

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TABLE 12.2 Heat-Treatment Requirements

Grade	Class	Austenitizing temperature, min, °F (°C)	Media*	Quenching cool below, °F (°C)	Tempering temperature, °F (°C)†
1	A	1600 (870)	A	450 (230)	1100 (595)
1	B	1600 (870)	L	500 (260)	1100 (595)
1	C	1600 (870)	A or L	500 (260)	1150 (620)
2	A	1600 (870)	A	450 (230)	1100 (595)
2	B	1600 (870)	L	500 (260)	1100 (595)
2	C	1600 (870)	A or L	500 (260)	1150 (620)
4	A	1600 (870)	A or L	500 (260)	1100 (595)
4	B	1600 (870)	L	500 (260)	1100 (595)
4	C	1600 (870)	A or L	500 (260)	1150 (620)
4	D	1600 (870)	L	500 (260)	1150 (620)
4	E	1600 (870)	L	500 (260)	1100 (595)
6	A	1550 (845)	A	500 (260)	1100 (595)
6	B	1550 (845)	L	500 (260)	1100 (595)
7	A	1650 (900)	L	600 (315)	1100 (595)
8	A	1750 (955)	A	500 (260)	1250 (675)
8	B	1750 (955)	L	500 (260)	1250 (675)
8	C	1750 (955)	L	500 (260)	1250 (675)
9	A	1600 (870)	A or L	500 (260)	1100 (595)
9	B	1600 (870)	L	500 (260)	1100 (595)
9	C	1600 (870)	A or L	500 (260)	1150 (620)
9	D	1600 (870)	L	500 (260)	1150 (620)
9	E	1600 (870)	L	500 (260)	1100 (595)
10	A	1550 (845)	A	500 (260)	1100 (595)
10	B	1550 (845)	L	500 (260)	1100 (595)
11	A	1650 (900)	A	600 (315)	1100 (595)
11	B	1650 (900)	L	600 (315)	1100 (595)
12	A	1750 (955)	A	600 (315)	1100 (595)
12	B	1750 (955)	L	400 (205)	1100 (595)
13	A	1550 (845)	A	500 (260)	1100 (595)
13	B	1550 (845)	L	500 (260)	1100 (595)
14	A	1550 (845)	L	500 (260)	1100 (595)
16	A	1600 (870)‡	A	600 (315)	1100 (595)
CA15	A	1750 (955)	A or L	400 (205)	900 (480)
CA15	B	1750 (955)	A or L	400 (205)	1100 (595)
CA15	C	1750 (955)	A or L	400 (205)	1150 (620)§
CA15	D	1750 (955)	A or L	400 (205)	1150 (260)§
CA15M	A	1750 (955)	A or L	400 (205)	1100 (595)
CA6NM	A	1850 (1010)	A or L	200 (95)	1050–1150 (565–620)
CA6NM	B	1850 (1010)	A or L	200 (95)	1225–1275 (665–690)§,¶ 1050–1150 (565–620)

* A = air, L = liquid.
† Minimum temperature unless range is specified.
‡ Double austenitize.
§ Double temper.
¶ Air cool to below 200°F (95°C) after first temper.
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TABLE 12.3 Required Mechanical Properties

Previous designation	Grade	Class	Tensile strength,* min, ksi (MPa)	Yield strength, min, ksi (MPa), at 0.2% offset	Elongation, 2 in (50 mm) or 4*d*, min, %	Reduction of area, min %	Hardness max, HRC	Max thickness, in (mm)
1N	1	A	85 (585)–110 (760)	55 (380)	22	40		
1Q	1	B	90 (620)–115 (795)	65 (450)	22	45		
	1	C	90 (620)	65 (450)	22	45	22 (235)	
2N	2	A	85 (585)–110 (760)	53 (365)	22	35		
2Q	2	B	90 (620)–115 (795)	65 (450)	22	40		
	2	C	90 (620)	65 (450)	22	40	22 (235)	
4N	4	A	90 (620)–115 (795)	60 (415)	18	40		
4Q	4	B	105 (725)–130 (895)	85 (585)	17	35		
	4	C	90 (620)	60 (415)	18	35	22 (235)	
	4	D	100 (690)	75 (515)	17	35	22 (235)	
4QA	4	E	115 (795)	95 (655)	15	35		
6N	6	A	115 (795)	80 (550)	18	30		
6Q	6	B	120 (825)	95 (655)	12	25		
7Q	7	A	115 (795)	100 (690)	15	30		2.5 (63.5)
8N	8	A	85 (585)–110 (760)	55 (380)	20	35		
8Q	8	B	105 (725)	85 (585)	17	30		
	8	C	100 (690)	75 (515)	17	35	22 (235)	
9N	9	A	90 (620)	60 (415)	18	35		
9Q	9	B	105 (725)	85 (585)	16	35		
	9	C	90 (620)	60 (415)	18	35	22 (235)	
	9	D	100 (690)	75 (515)	17	35	22 (235)	
	9	E	115 (795)	95 (655)	15	35		
10N	10	A	100 (690)	70 (485)	18	35		
10Q	10	B	125 (860)	100 (690)	15	35		

TABLE 12.3 Required Mechanical Properties (*Continued*)

Previous designation	Grade	Class	Tensile strength,* min, ksi (MPa)	Yield strength, min, ksi (MPa), at 0.2% offset	Elongation, 2 in (50 mm) or 4*d*, min, %	Reduction of area, min %	Hardness max, HRC	Max thickness, in (mm)
11N	11	A	70 (484)–95 (655)	40 (275)	20	35		
11Q	11	B	105 (725)–130 (895)	85 (585)	17	35		
12N	12	A	70 (485)–95 (655)	40 (275)	20	35		
12Q	12	B	105 (725)–130 (895)	85 (585)	17	35		
13N	13	A	90 (620)–115 (795)	60 (415)	18	35		
13Q	13	B	105 (725)–130 (895)	85 (585)	17	35		
14Q	14	A	120 (825)–145 (1000)	95 (655)	14	30		
16N	16	A	70 (485)–95 (655)	40 (275)	22	35		
CA15A	CA15	A	140 (965)–170 (1170)	110 (760)–130 (895)	10	25		
CA15	CA15	B	90 (620)–115 (795)	65 (450)	18	30		
	CA15	C	90 (620)	60 (415)	18	35	22 (235)	
	CA15	D	100 (690)	75 (515)	17	35	22 (235)	
CA15M	CA15M	A	90 (620)–115 (795)	65 (450)	18	30		
CA6NM	CA6NM	A	110 (760)–135 (930)	80 (515)	15	35		
CA6NM	CA6NM	B	100 (690)	75 (520)	17	35	23 (255)†	

* Minimum ksi, unless range is given.

† Test Methods and Definitions A 370, Table 3a does not apply to CA6NM. The conversion given is based on CA6NM test coupons. (For example, see ASTM STP 756.)

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TABLE 12.4 Heat-Treatment Requirements

Grade	Heat treatment
CF-8, CG-8M, CG-12, CF-20, CF-8M CF-8C, CF-16F, CF-16Fa	Heat to 1900°F (1040°C) minimum, hold for sufficient time to heat casting to temperature, quench in water or rapid cool by other means so as to develop acceptable corrosion resistance.
CH-20, CE-30, CK-20	Heat to 2000°F (1093°C) minimum, hold for sufficient time to heat casting to temperature, quench in water or rapid cool by other means so as to develop acceptable corrosion resistance.
CA-15, CA-15M, CA-40, CA-40F	(1) Heat to 1750°F (955°C) minimum, air cool and temper at 1100°F (595°C) minimum, or (2) Anneal at 1450°F (790°C) minimum.
CB-30, CC-50	(1) Heat to 1450°F (790°C) minimum, and air cool, or (2) Heat to 1450°F (790°C) minimum, and furnace cool.
CF-3, CF-3M, CF-3MN	(1) Heat to 1900°F (1040°C) minimum, hold for sufficient time to heat casting to temperature, and cool rapidly so as to develop acceptable corrosion resistance, or (2) As cast if corrosion resistance is acceptable.
CN-3M	Heat to 2150°F (1175°C) minimum, hold for sufficient time to heat casting to temperature, quench in water or rapid cool by other means so as to develop acceptable corrosion resistance.
CN-7M, CG-6MMN	Heat to 2050°F (1120°C) minimum, hold for sufficient time to heat casting to temperature, quench in water or rapid cool by other means so as to develop acceptable corrosion resistance.
CN-7MS	Heat to 2100°F (1150°C) minimum, 2150°F (1180°C) maximum, hold for sufficient time (2 h minimum) to heat casting to temperature and quench in water to develop acceptable corrosion resistance.
CA-6NM	Heat to 1750°F (955°C) minimum, air cool to 200°F (95°C) or lower prior to any optional intermediate temper and prior to the final temper. The final temper shall be between 1050°F (565°C) and 1150°F (620°C).
CD-4MCu	Heat to 1900°F (1040°C) minimum, hold for sufficient time to heat casting uniformly to temperature, quench in water or rapid cool by other means to develop acceptable corrosion resistance.
CA-6N	Heat to 1900°F (1040°C), air cool, reheat to 1500°F (815°C), air cool, and age at 800°F (425°C), holding at each temperature sufficient time to heat casting uniformly to temperature.
CF10SMnN	Heat to 1950°F (1065°C) minimum, hold for sufficient time to heat casting to temperature, quench in water or rapid cool by other means so as to develop acceptable corrosion resistance.
CA-28MWV	(1) Heat to 1875–1925°F (1025–1050°C), quench in air or oil, and temper at 1150°F (620°C) minimum, or (2) Anneal at 1400°F (760°C) minimum.
CK-3MCuN	Heat to 2100°F (1150°C) minimum, hold for sufficient time to heat casting to temperature, quench in water or rapid cool by other means so as to develop acceptable corrosion resistance.

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TABLE 12.5 Preheat and Tensile Requirements

Minimum preheat temperatures		
	Minimum preheat temperatures	
Grade	°F	°C
CA-15, CA-15M CA-40, CA-28MWV	400	[205]
Others	50	[10]

Tensile requirements							
		Tensile strength, min		Yield strength, min		Elongation in 2 in (50 mm), min, %*	Reduction of area, min, %
Grade	Type	ksi	MPa	ksi	MPa		
CF-8	19 Chromium, 9 Nickel	70†	485†	30†	205†	35	—
CG-12	22 Chromium, 12 Nickel	70	485	28	195	35	—
CF-20	19 Chromium, 9 Nickel	70	485	30	205	30	—
CF-8M	19 Chromium, 10 Nickel, with molybdenum	70	485	30	205	30	—
CF-8C	19 Chromium, 10 Nickel with columbium	70	485	30	205	30	—
CF-16 and CF-16Fa	19 Chromium, 9 Nickel, free machining	70	485	30	205	30	—
CH-20 and CH-10	25 Chromium, 12 Nickel	70	485	30	205	30	—
CK-20	25 Chromium, 20 Nickel	65	450	28	195	30	—
CE-30	29 Chromium, 9 Nickel	80	550	40	275	10	—
CA-15 and CA-15M	12 Chromium	90	620	65	450	18	30

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CB-30	20 Chromium	65	450	30	205	—	—
CC-50	28 Chromium	55	380	—	—	—	—
CA-40	12 Chromium	100	690	70	485	15	25
CA-40F	12 Chromium, free machining	100	690	70	485	12	—
CF-3	19 Chromium, 9 nickel	70	485	30	205	35	—
CF10SMnN	17 Chromium, 8.5 nickel with nitrogen 9 Nickel	85	585	42	290	30	—
CF-3M	19 Chromium, 10 Nickel, with molybdenum	70	485	30	205	30	—
CF-3MN	19 Chromium, 10 Nickel, with molybdenum, and nitrogen	75	515	37	255	35	—
CG6MMN	Chromium-nickel-manganese-molybdenum	85	585	42	290	30	—
CG-8M	19 Chromium, 11 Nickel, with molybdenum	75	520	35	240	25	—
CN-3M		63	435	25	170	30	—
CN-7M	20 Chromium, 29 Nickel, with copper and molybdenum	62	425	25	170	35	—
CN-7MS	19 Chromium, 24 Nickel, with copper and molybdenum	70	485	30	205	35	—
CA-6NM	12 Chromium, 4 nickel	110	755	80	550	15	35
CD-4MCu		100	690	70	485	16	
CA-6N	11 Chromium, 7 nickel	140	965	135	930	15	50
CA-28MWV‡	12 Chromium, with molybdenum, tungsten, and vanadium	140	965	110	760	10	24
CK-3MCuN	20 Chromium 18 Nickel, with copper and molybdenum	80	550	38	260	35	—

* When ICI test bars are used in tensile testing as provided for in this specification, the gage length to reduced section diameter ratio shall be 4:1.

† For low ferrite or nonmagnetic castings of this grade, the following values shall apply; tensile strength, min, 65 ksi (450 MPa); yield point, min, 28 ksi (195 MPa).

‡ These mechanical properties apply only when heat treatment (1) has been used.

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TABLE 12.6 Brinell Hardness Numbers*

(Ball 10 mm in diameter, applied loads of 500, 1500, and 3000 kgf)

Brinell hardness number				Brinell hardness number				Brinell hardness number				Brinell hardness number			
Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load	Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load	Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load	Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load
2.00	158	473	945	2.60	92.6	278	555	3.20	60.5	182	363	3.80	42.4	127	255
2.01	156	468	936	2.61	91.8	276	551	3.21	60.1	180	361	3.81	42.2	127	253
2.02	154	463	926	2.62	91.1	273	547	3.22	59.8	179	359	3.82	42.0	126	252
2.03	153	459	917	2.63	90.4	271	543	3.23	59.4	178	356	3.83	41.7	125	250
2.04	151	454	908	2.64	89.7	269	538	3.24	59.0	177	354	3.84	41.5	125	249
2.05	150	450	899	2.65	89.0	267	534	3.25	58.6	176	352	3.85	41.3	124	248
2.06	148	445	890	2.66	88.4	265	530	3.26	58.3	175	350	3.86	41.1	123	246
2.07	147	441	882	2.67	87.7	263	526	3.27	57.9	174	347	3.87	40.9	123	245
2.08	146	437	873	2.68	87.0	261	522	3.28	57.5	173	345	3.88	40.6	122	244
2.09	144	432	865	2.69	86.4	259	518	3.29	57.2	172	343	3.89	40.4	121	242
2.10	143	428	856	2.70	85.7	257	514	3.30	56.8	170	341	3.90	40.2	121	241
2.11	141	424	848	2.71	85.1	255	510	3.31	56.5	169	339	3.91	40.0	120	240
2.12	140	420	840	2.72	84.4	253	507	3.32	56.1	168	337	3.92	39.8	119	239
2.13	139	416	832	2.73	83.8	251	503	3.33	55.8	167	335	3.93	39.6	119	237
2.14	137	412	824	2.74	83.2	250	499	3.34	55.4	166	333	3.94	39.4	118	236
2.15	136	408	817	2.75	82.6	248	495	3.35	55.1	165	331	3.95	39.1	117	235
2.16	135	404	809	2.76	81.9	246	492	3.36	54.8	164	329	3.96	38.9	117	234
2.17	134	401	802	2.77	81.3	244	488	3.37	54.4	163	326	3.97	38.7	116	232
2.18	132	397	794	2.78	80.8	242	485	3.38	54.1	162	325	3.98	38.5	116	231
2.19	131	393	787	2.79	80.2	240	481	3.39	53.8	161	323	3.99	38.3	115	230
2.20	130	390	780	2.80	79.6	239	477	3.40	53.4	160	321	4.00	38.1	114	229
2.21	129	386	772	2.81	79.0	237	474	3.41	53.1	159	319	4.01	37.9	114	228

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2.22	128	383	765	2.82	78.4	235	471	3.42	52.8	158	317	4.02	37.7	113	226
2.23	126	379	758	2.83	77.9	234	467	3.43	52.5	157	315	4.03	37.5	113	225
2.24	125	376	752	2.84	77.3	232	464	3.44	52.2	156	313	4.04	37.3	112	224
2.25	124	372	745	2.85	76.8	230	461	3.45	51.8	156	311	4.05	37.1	111	223
2.26	123	369	738	2.86	76.2	229	457	3.46	51.5	155	309	4.06	37.0	111	222
2.27	122	366	732	2.87	75.7	227	454	3.47	51.2	154	307	4.07	36.8	110	221
2.28	121	363	725	2.88	75.1	225	451	3.48	50.9	153	306	4.08	36.6	110	219
2.29	120	359	719	2.89	74.6	224	448	3.49	50.6	152	304	4.09	36.4	109	218
2.30	119	356	712	2.90	74.1	222	444	3.50	50.3	151	302	4.10	36.2	109	217
2.31	118	353	706	2.91	73.6	221	441	3.51	50.0	150	300	4.11	36.0	108	216
2.32	117	350	700	2.92	73.0	219	438	3.52	49.7	149	298	4.12	35.8	108	215
2.33	116	347	694	2.93	72.5	218	435	3.53	49.4	148	297	4.13	35.7	107	214
2.34	115	344	688	2.94	72.0	216	432	3.54	49.2	147	295	4.14	35.5	106	213
2.35	114	341	682	2.95	71.5	215	429	3.55	48.9	147	293	4.15	35.3	106	212
2.36	113	338	676	2.96	71.0	213	426	3.56	48.6	146	292	4.16	35.1	105	211
2.37	112	335	670	2.97	70.5	212	423	3.57	48.3	145	290	4.17	34.9	105	210
2.38	111	332	665	2.98	70.1	210	420	3.58	48.0	144	288	4.18	34.8	104	209
2.39	110	330	659	2.99	69.6	209	417	3.59	47.7	143	286	4.19	34.6	104	208
2.40	109	327	653	3.00	69.1	207	415	3.60	47.5	142	285	4.20	34.4	103	207
2.41	108	324	648	3.01	68.6	206	412	3.61	47.2	142	283	4.21	34.2	103	205
2.42	107	322	643	3.02	68.2	205	409	3.62	46.9	141	282	4.22	34.1	102	204
2.43	106	319	637	3.03	67.7	203	406	3.63	46.7	140	280	4.23	33.9	102	203
2.44	105	316	632	3.04	67.3	202	404	3.64	46.4	139	278	4.24	33.7	101	202
2.45	104	313	627	3.05	66.8	200	401	3.65	46.1	138	277	4.25	33.6	101	201
2.46	104	311	621	3.06	66.4	199	398	3.66	45.9	138	275	4.26	33.4	100	200
2.47	103	308	616	3.07	65.9	198	395	3.67	45.6	137	274	4.27	33.2	99.7	199
2.48	102	306	611	3.08	65.5	196	393	3.68	45.4	136	272	4.28	33.1	99.2	198
2.49	101	303	606	3.09	65.0	195	390	3.69	45.1	135	271	4.29	32.9	98.8	198
2.50	100	301	601	3.10	64.6	194	388	3.70	44.9	135	269	4.30	32.8	98.3	197
2.51	99.4	298	597	3.11	64.2	193	385	3.71	44.6	134	268	4.31	32.6	97.8	196
2.52	98.6	296	592	3.12	63.8	191	383	3.72	44.4	133	266	4.32	32.4	97.3	195
2.53	97.8	294	587	3.13	63.3	190	380	3.73	44.1	132	265	4.33	32.3	96.8	194
2.54	97.1	291	582	3.14	62.9	189	378	3.74	43.9	132	263	4.34	32.1	96.4	193
2.55	96.3	289	578	3.15	62.5	188	375	3.75	43.6	131	262	4.35	32.0	95.9	192

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TABLE 12.6 Brinell Hardness Numbers* (*Continued*)

Brinell hardness number				Brinell hardness number				Brinell hardness number				Brinell hardness number			
Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load	Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load	Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load	Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load
2.56	95.5	287	573	3.16	62.1	186	373	3.76	43.4	130	260	4.36	31.8	95.5	191
2.57	94.8	284	569	3.17	61.7	185	370	3.77	43.1	129	259	4.37	31.7	95.0	190
2.58	94.0	282	564	3.18	61.3	184	368	3.78	42.9	129	257	4.38	31.5	94.5	189
2.59	93.3	280	560	3.19	60.9	183	366	3.79	42.7	128	256	4.39	31.4	94.1	188
4.40	31.2	93.6	187	5.05	23.3	69.8	140	5.70	17.8	53.5	107	6.35	14.0	42.0	84.0
4.41	31.1	93.2	186	5.06	23.2	69.5	139	5.71	17.8	53.3	107	6.36	13.9	41.8	83.7
4.42	30.9	92.7	185	5.07	23.1	69.2	138	5.72	17.7	53.1	106	6.37	13.9	41.7	83.4
4.43	30.8	92.3	185	5.08	23.0	68.9	138	5.73	17.6	52.9	106	6.38	13.8	41.5	83.1
4.44	30.6	91.8	184	5.09	22.9	68.6	137	5.74	17.6	52.7	105	6.39	13.8	41.4	82.8
4.45	30.5	91.4	183	5.10	22.8	68.3	137	5.75	17.5	52.5	105	6.40	13.7	41.2	82.5
4.46	30.3	91.0	182	5.11	22.7	68.0	136	5.76	17.4	52.3	105	6.41	13.7	41.1	82.2
4.47	30.2	90.5	181	5.12	22.6	67.7	135	5.77	17.4	52.1	104	6.42	13.6	40.9	81.9
4.48	30.0	90.1	180	5.13	22.5	67.4	135	5.78	17.3	51.9	104	6.43	13.6	40.8	81.6
4.49	29.9	89.7	179	5.14	22.4	67.1	134	5.79	17.2	51.7	103	6.44	13.5	40.6	81.3
4.50	29.8	89.3	179	5.15	22.3	66.9	134	5.80	17.2	51.5	103	6.45	13.5	40.5	81.0
4.51	29.6	88.8	178	5.16	22.2	66.6	133	5.81	17.1	51.3	103	6.46	13.4	40.4	80.7
4.52	29.5	88.4	177	5.17	22.1	66.3	133	5.82	17.0	51.1	102	6.47	13.4	40.2	80.4
4.53	29.3	88.0	176	5.18	22.0	66.0	132	5.83	17.0	50.9	102	6.48	13.4	40.1	80.1
4.54	29.2	87.6	175	5.19	21.9	65.8	132	5.84	16.9	50.7	101	6.49	13.3	39.9	79.8
4.55	29.1	87.2	174	5.20	21.8	65.5	131	5.85	16.8	50.5	101	6.50	13.3	39.8	79.6
4.56	28.9	86.8	174	5.21	21.7	65.2	130	5.86	16.8	50.3	101	6.51	13.2	39.6	79.3
4.57	28.8	86.4	173	5.22	21.6	64.9	130	5.87	16.7	50.2	100	6.52	13.2	39.5	79.0

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4.58	28.7	86.0	172	5.23	21.6	64.7	129	5.88	16.7	50.0	99.9	6.53	13.1	39.4	78.7
4.59	28.5	85.6	171	5.24	21.5	64.4	129	5.89	16.6	49.8	99.5	6.54	13.1	39.2	78.4
4.60	28.4	85.4	170	5.25	21.4	64.1	128	5.90	16.5	49.6	99.2	6.55	13.0	39.1	78.2
4.61	28.3	84.8	170	5.26	21.3	63.9	128	5.91	16.5	49.4	98.8	6.56	13.0	38.9	78.0
4.62	28.1	84.4	169	5.27	21.2	63.6	127	5.92	16.4	49.2	98.4	6.57	12.9	38.8	77.6
4.63	28.0	84.0	168	5.28	21.1	63.3	127	5.93	16.3	49.0	98.0	6.58	12.9	38.7	77.3
4.64	27.9	83.6	167	5.29	21.0	63.1	126	5.94	16.3	48.8	97.7	6.59	12.8	38.5	77.1
4.65	27.8	83.3	167	5.30	20.9	62.8	126	5.95	16.2	48.7	97.3	6.60	12.8	38.4	76.8
4.66	27.6	82.9	166	5.31	20.9	62.6	125	5.96	16.2	48.5	96.9	6.61	12.8	38.3	76.5
4.67	27.5	82.5	165	5.32	20.8	62.3	125	5.97	16.1	48.3	96.6	6.62	12.7	38.1	76.2
4.68	27.4	82.1	164	5.33	20.7	62.1	124	5.98	16.0	48.1	96.2	6.63	12.7	38.0	76.0
4.69	27.3	81.8	164	5.34	20.6	61.8	124	5.99	16.0	47.9	95.9	6.64	12.6	37.9	75.7
4.70	27.1	81.4	163	5.35	20.5	61.5	123	6.00	15.9	47.7	95.5	6.65	12.6	37.7	75.4
4.71	27.0	81.0	162	5.36	20.4	61.3	123	6.01	15.9	47.6	95.1	6.66	12.5	37.6	75.2
4.72	26.9	80.7	161	5.37	20.3	61.0	122	6.02	15.8	47.4	94.8	6.67	12.5	37.5	74.9
4.73	26.8	80.3	161	5.38	20.3	60.8	122	6.03	15.7	47.2	94.4	6.68	12.4	37.3	74.7
4.74	26.6	79.9	160	5.39	20.2	60.6	121	6.04	15.7	47.0	94.1	6.69	12.4	37.2	74.4
4.75	26.5	79.6	159	5.40	20.1	60.3	121	6.05	15.6	46.8	93.7	6.70	12.4	37.1	74.1
4.76	26.4	79.2	158	5.41	20.0	60.1	120	6.06	15.6	46.7	93.4	6.71	12.3	36.9	73.9
4.77	26.3	78.9	158	5.42	19.9	59.8	120	6.07	15.5	46.5	93.0	6.72	12.3	36.8	73.6
4.78	26.2	78.5	157	5.43	19.9	59.6	119	6.08	15.4	46.3	92.7	6.73	12.2	36.7	73.4
4.79	26.1	78.2	156	5.44	19.8	59.3	119	6.09	15.4	46.2	92.3	6.74	12.2	36.6	73.1
4.80	25.9	77.8	156	5.45	19.7	59.1	118	6.10	15.3	46.0	92.0	6.75	12.1	36.4	72.8
4.81	25.8	77.5	155	5.46	19.6	58.9	118	6.11	15.3	45.8	91.7	6.76	12.1	36.3	72.6
4.82	25.7	77.1	154	5.47	19.5	58.6	117	6.12	15.2	45.7	91.3	6.77	12.1	36.2	72.3
4.83	25.6	76.8	154	5.48	19.5	58.4	117	6.13	15.2	45.5	91.0	6.78	12.0	36.0	72.1
4.84	25.5	76.4	153	5.49	19.4	58.2	116	6.14	15.1	45.3	90.6	6.79	12.0	35.9	71.8
4.85	25.4	76.1	152	5.50	19.3	57.9	116	6.15	15.1	45.2	90.3	6.80	11.9	35.8	71.6
4.86	25.3	75.8	152	5.51	19.2	57.7	115	6.16	15.0	45.0	90.0	6.81	11.9	35.7	71.3
4.87	25.1	75.4	151	5.52	19.2	57.5	115	6.17	14.9	44.8	89.6	6.82	11.8	35.5	71.1
4.88	25.0	75.1	150	5.53	19.1	57.2	114	6.18	14.9	44.7	89.3	6.83	11.8	35.4	70.8
4.89	24.9	74.8	150	5.54	19.0	57.0	114	6.19	14.8	44.5	89.0	6.84	11.8	35.3	70.6
4.90	24.8	74.4	149	5.55	18.9	56.8	114	6.20	14.7	44.3	88.7	6.86	11.7	35.2	70.4
4.91	24.7	74.1	148	5.56	18.9	56.6	113	6.21	14.7	44.2	88.3	6.86	11.7	35.1	70.1

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TABLE 12.6 Brinell Hardness Numbers* (*Continued*)

Brinell hardness number				Brinell hardness number				Brinell hardness number				Brinell hardness number			
Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load	Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load	Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load	Diameter of indentation, mm	500-kgf load	1500-kgf load	3000-kgf load
4.92	24.6	73.8	148	5.57	18.8	56.3	113	6.22	14.7	44.0	88.0	6.87	11.6	34.9	69.9
4.93	24.5	73.5	147	5.58	18.7	56.1	112	6.23	14.6	43.8	87.7	6.88	11.6	34.8	69.6
4.94	24.4	73.2	146	5.59	18.6	55.9	112	6.24	14.6	43.7	87.4	6.89	11.6	34.7	69.4
4.95	24.3	72.8	146	5.60	18.6	55.7	111	6.25	14.5	43.5	87.1	6.90	11.5	34.6	69.2
4.96	24.2	72.5	145	5.61	18.5	55.5	111	6.26	14.5	43.4	86.7	6.91	11.5	34.5	68.9
4.97	24.1	72.2	144	5.62	18.4	55.2	110	6.27	14.4	43.2	86.4	6.92	11.4	34.3	68.7
4.98	24.0	71.9	144	5.63	18.3	55.0	110	6.28	14.4	43.1	86.1	6.93	11.4	34.2	68.4
4.99	23.9	71.6	143	5.64	18.3	54.8	110	6.29	14.3	42.9	85.8	6.94	11.4	34.1	68.2
5.00	23.8	71.3	143	5.65	18.2	54.6	109	6.30	14.2	42.7	85.5	6.95	11.3	34.0	68.0
5.01	23.7	71.0	142	5.66	18.1	54.4	109	6.31	14.2	42.6	85.2	6.96	11.3	33.9	67.7
5.02	23.6	70.7	141	5.67	18.1	54.2	108	6.32	14.1	42.4	84.9	6.97	11.3	33.8	67.5
5.03	23.5	70.4	141	5.68	18.0	54.0	108	6.33	14.1	42.3	84.6	6.98	11.2	33.6	67.3
5.04	23.4	70.1	140	5.69	17.9	53.7	107	6.34	14.0	42.1	84.3	6.99	11.2	33.5	67.0

* Prepared by the Engineering Mechanics Section, Institute for Standards Technology.

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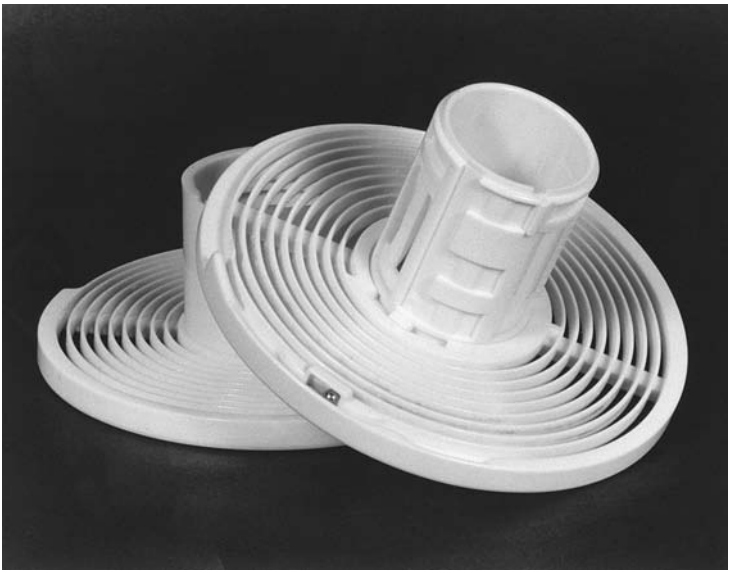

Figure 12.20 Typical intricate plastic-cast parts.

materials such as glass, carbon, and mineral fibers for added strength. Thermoset plastics usually are more dimensionally stable and heat resistant and have better electrical properties than thermoplastics.

Complex molded shapes of the plastics are analyzed today using the advanced finite-element analysis (FEA) techniques available for the personal computer and engineering design stations. Figure 12.20 shows a typical intricate plastic part that must be dimensionally accurate as well as chemical resistant.

12.5.1 Prototypes of the plastics

Building a prototype plastic part is a compromise because the part is usually machined from plastic blocks and slabs and will not duplicate the exact performance of the finished part, which is made in a mold. The closest duplicate to a plastic production part is made by molding a prototype in mild-steel molds made specifically for the prototype. This method is expensive but is the closest method to use if you wish to avoid expensive rework or changes to a finished production mold. This approach will give the most accurate test results prior to building the actual production mold.

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12.5.2 Properties and characteristics of modern plastics

Widely used plastics are discussed in Chap. 4, "Materials and Their Uses." The applications of the modern plastics are given there, as well as the trade names and families of all plastics manufactured today.

12.5.3 Design of molded plastic parts

Final selection of plastic type and part configuration or design should be reviewed and coordinated with the mold maker and plastic part manufacturer before the final design drawings are made. Mold makers and molded-part manufacturers can alert the designer to the many problem areas that are prevalent on preliminary designs for plastic parts.

Plastic part design handbooks are available from all the leading producers of plastic materials, such as DuPont, General Electric, Monsanto, etc. These manuals or handbooks cover detail design, appropriate calculation techniques, and complete chemical, physical, and electrical properties of the materials. The design handbooks may be secured by writing directly to the plastics sections of the large suppliers or their distributors.

12.5.4 Plastics molding machinery and molds

A great many machines are made for molding plastic parts, most of which are expensive and require specialized techniques for operation. Figures 12.21 and 12.22 show a typical group of machines required for producing parts made of cycloaliphatic epoxy. This class of thermoset plastic has gained wide recognition in the electrical power distribution industry for parts that support or brace high-voltage current-carrying busses and parts of switching devices such as breakers and switches of all classes up to 34.5 kV. Figure 12.21 shows the mixing and dispensing machine, and Fig. 12.22 shows the complete group of equipment, with the mold-clamping machine at the front of the photograph.

Because of the high injection pressures developed in this plastic molding process, the clamping machine must exert a high load on the mold to prevent it from opening during the injection process. In this process, the hot, molten plastic is injected under pressure into the mold, where it is held for the "curing" or setting time prior to being released from the mold. In the molding of cycloaliphatic epoxy after the proper cure, the plastic part is removed from the mold,

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Figure 12.21 Mixing and dispensing sections of epoxy casting equipment.

Figure 12.22 Complete assembly of epoxy casting machinery: (*far left*) oven, (*center*) die-clamping machine, (*far right*) dispensing section, (*center*) background process control panel (CNC).

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placed in an oven set to a preselected temperature, and baked for a predetermined time interval. Cycloaliphatic epoxy is being used in the electrical industries as a substitute for wet-process porcelain, which for many years was one of the few materials available for this type of service. Glass and polyester-glass thermosets are also used in electrical applications, as are other electrical-grade epoxies.

The tonnage and size of the clamping machine for injection molding plastics are determined by the volume of plastic to be injected at one time (a single *shot*). A machine that handles parts up to 20 in^3 would be considered of moderate size, whereas a machine required to injection mold parts with a volume of 60 in^3 would be considered large. Clamping machines are made in sizes up to hundreds of tons of clamping capacity, and these machines usually are found at the larger plastic molding manufacturers.

12.6 Extrusions

An extruded shape is one in which the material being extruded is pushed, under high pressure and high temperature, through a set of extrusion dies that have the shape of a cross section of the part. Extrusion is similar to drawing, except that in drawing the drawn part is pulled out of or through the dies or series of dies of progressive sizes. The material is cold worked more effectively when it is drawn rather than extruded.

Aluminum alloys are particularly well suited for the extrusion processes. Very large, high-tonnage extrusion presses are required for the extrusion of aluminum and its alloys. Generally, two classes or grades of aluminum extrusions are widely available: structural aluminum and architectural aluminum shapes. These two classes of extrusions are available in the following alloys and tempers:

Class	Shape	Alloy, temper, and specification
Structural	Angles	6061-T6, ASTM B308
	Channels	6061-T6, ASTM B308
	Tees	6061-T6, ASTM B308
	Zees	6061-T6, ASTM B308
	H beams and I beams	6061-T6, ASTM B308
	Wide-flange beams	6061-T6, ASTM B308
Architectural	Angles	6063-T52, ASTM B221
	Channels	6063-T52, ASTM B221
	Tees	6063-T52, ASTM B221
	Zees	6063-T52, ASTM B221

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Aluminum alloy extrusions are also available in the following standard shapes:

- Round rod
- Square bar
- Rectangular bar
- Hexagonal bar
- Round tube
- Square tube
- Rectangular tube

The alloy designations of the above-listed shapes may be one of the following:

- 2011
- 2017
- 2024
- 6061
- 6063

An aluminum alloy extrusion may be designed to any practical shape that the extrusion dies may accommodate, and shapes usually are limited to the designer's imagination and ingenuity and the size of the part. Some of the standard extruded shapes that are available from various sources nationwide are shown in Fig. 12.23. The temper designations and lengths available are also shown in the figure.

A table of distances across flats for squares, hexagons, and octagons is given in Fig. 12.24. This will prove useful and time saving when these dimensions need to be known and you do not wish to calculate them by using the figures shown in Chap. 2 of this *Handbook*.

Plastic extrusions. A great many plastic-extruded shapes are available from the plastic manufacturers, whose catalogs may be obtained through such trade magazines as *The American Machinist, Machine Design, Product Design and Development, Modern Machine Shop,* and others. If you work with or need plastic-extruded shapes, keep a

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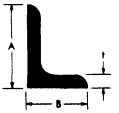
STANDARD ANGLES ①

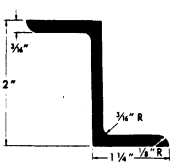


ANGLES—UNEQUAL LEGS, EXTRUDED
Alloy 6061-T6 • Length—25 ft

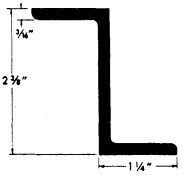
Dimensions, in.			Est wt per ft, lb
A	B	t	
N 1-1/4	3/4	3/32	.21
N 1-1/4	1	1/8	.31
N 1-1/2	3/4	1/8	.31
1-1/2	3/4	N 3/16	.46
N 1-1/2	1	5/32	.43
1-1/2	1	N 1/4	.66
1-1/2	1-1/4	1/8	.38
1-1/2	1-1/4	3/16	.57
1-1/2	1-1/4	1/4	.74
1-3/4	1-1/4	1/8	.42
1-3/4	1-1/4	3/16	.62
1-3/4	1-1/4	1/4	.81
2	1-1/2	1/8	.50
2	1-1/2	3/16	.73
2	1-1/2	1/4	.96
2	1-1/2	3/8	1.38
N 2-1/2	1-1/2	3/16	.85
2-1/2	1-1/2	1/4	1.11
2-1/2	1-1/2	N 5/16	1.36
2-1/2	2	1/8	.65
2-1/2	2	3/16	.96
2-1/2	2	1/4	1.26
2-1/2	2	5/16	1.55
2-1/2	2	3/8	1.83
3	2	3/16	1.07
3	2	1/4	1.40
3	2	5/16	1.73
3	2	3/8	2.05
3	2	N 7/16	2.35
3	2-1/2	1/4	1.54
3	2-1/2	5/16	1.90
3	2-1/2	3/8	2.25
3-1/2	2-1/2	1/4	1.68
3-1/2	2-1/2	5/16	2.08
3-1/2	2-1/2	3/8	2.47
3-1/2	2-1/2	N 1/2	3.23
3-1/2	3	1/4	1.84
3-1/2	3	5/16	2.28
3-1/2	3	N 3/8	2.70
4	3	1/4	1.99
4	3	5/16	2.46
4	3	3/8	2.93
4	3	1/2	3.83
4	3	5/8	4.69
N 4	3-1/2	3/8	3.13
4	3-1/2	N 1/2	4.10
5	3	3/8	3.35
5	3	1/2	4.40
5	3-1/2	5/16	3.01
5	3-1/2	3/8	3.58
5	3-1/2	N 7/16	4.15
5	3-1/2	1/2	4.70
5	3-1/2	5/8	5.79
6	3-1/2	5/16	3.39
6	3-1/2	N 3/8	4.04
6	3-1/2	1/2	5.31
6	4	3/8	4.24
6	4	N 7/16	4.91
6	4	1/2	5.58
6	4	5/8	6.88
6	4	3/4	8.48
N 8	6	5/8	9.84
8	6	N 11/16	10.76
8	6	3/4	11.68

① Angle sections listed as "standard" are approximations of American Standard sections. For elements of sections and detailed dimensions, consult *Alcoa Structural Handbook*.
N Not stocked at plant.

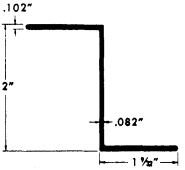
ZEES, EXTRUDED



ZEE 771-C
Alloy 6061-T6 • Length—22 ft
Est wt per ft—.938 lb

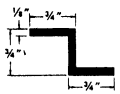


ZEE 7088
Alloy 6061-T6 • Length—22 ft
Est wt per ft—1.022 lb

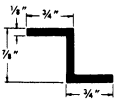


ZEE 45876
Alloy 6063-T6 • Length—24 ft
Est wt per ft—.498 lb

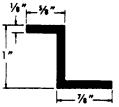
ZEE 205741
Alloy 6063-T52 • Length—16 ft
Est wt per ft—.148 lb



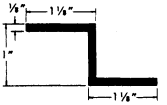
ZEE 205751
Alloy 6063-T52 • Length—16 ft
Est wt per ft—.300 lb



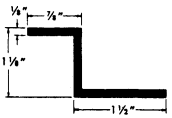
ZEE 23787
Alloy 6063-T52 • Length—16 ft
Est wt per ft—.319 lb



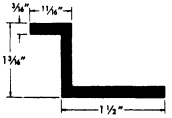
ZEE 205761
Alloy 6063-T52 • Length—16 ft
Est wt per ft—.337 lb



ZEE 4374
Alloy 6063-T52 • Length—16 ft
Est wt per ft—.450 lb



ZEE 205771
Alloy 6063-T52 • Length—16 ft
Est wt per ft—.487 lb



ZEE 7487
Alloy 6063-T52 • Length—16 ft
Est wt per ft—.676 lb

Figure 12.23 Samples of standard aluminum-extruded shapes.

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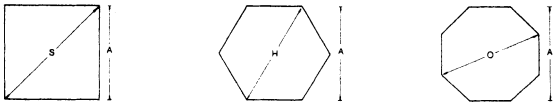
DISTANCES ACROSS CORNERS OF SQUARES, HEXAGONS & OCTAGONS



S=1.414A H=1.155A O=1.082A

A Size in Inches	Distance Across Corners in inches S Square	H Hexagon	O Octagon
1/8	.177	.144	.135
3/16	.265	.217	.203
1/4	.354	.289	.271
5/16	.442	.361	.338
3/8	.530	.433	.406
7/16	.619	.505	.474
1/2	.707	.577	.541
9/16	.795	.650	.609
5/8	.884	.722	.677
11/16	.972	.794	.744
3/4	1.061	.866	.812
13/16	1.149	.938	.879
7/8	1.237	1.010	.947
15/16	1.326	1.083	1.015
1	1.414	1.155	1.082
1 1/16	1.503	1.227	1.150
1 1/8	1.591	1.299	1.218
1 3/16	1.679	1.371	1.285
1 1/4	1.768	1.443	1.353
1 5/16	1.856	1.516	1.421
1 3/8	1.945	1.588	1.488
1 7/16	2.033	1.660	1.556
1 1/2	2.121	1.732	1.624
1 9/16	2.210	1.804	1.691
1 5/8	2.298	1.876	1.759
1 11/16	2.386	1.949	1.827
1 3/4	2.475	2.021	1.894
1 13/16	2.563	2.093	1.962
1 7/8	2.652	2.165	2.031
1 15/16	2.740	2.237	2.097
2	2.828	2.309	2.165
2 1/16	2.917	2.382	2.232
2 1/8	3.005	2.454	2.300
2 3/16	3.094	2.526	2.368
2 1/4	3.182	2.598	2.435
2 5/16	3.270	2.670	2.503
2 3/8	3.359	2.742	2.571
2 7/16	3.447	2.815	2.638
2 1/2	3.536	2.887	2.706
2 9/16	3.624	2.959	2.774
2 5/8	3.712	3.031	2.841
2 11/16	3.801	3.103	2.909
2 3/4	3.889	3.175	2.977
2 13/16	3.977	3.248	3.044
2 7/8	4.066	3.320	3.112
2 15/16	4.154	3.392	3.180
3	4.243	3.464	3.247
3 1/8	4.419	3.608	3.383
3 1/4	4.596	3.753	3.518
3 3/8	4.773	3.897	3.653
3 1/2	4.950	4.041	3.788
3 5/8	5.126	4.186	3.924
3 3/4	5.303	4.330	4.059
3 7/8	5.480	4.474	4.194
4	5.657	4.619	4.330
4 1/4	6.010	4.907	4.600
4 1/2	6.364	5.196	4.871
4 3/4	6.717	5.485	5.141
5	7.071	5.774	5.412
5 1/4	7.425	6.062	5.683
5 1/2	7.778	6.351	5.953
5 3/4	8.132	6.640	6.224
6	8.485	6.928	6.494

Figure 12.24 Dimensions of squares, hexagons, and octagons.

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series of these catalogs in your reference files. The plastic-extruded shapes not only make the design job easier, but they also enhance the appearance of the final product and facilitate assembly in many cases.

12.7 Powder-Metal Technology

Powder-metal parts are made by compressing a highly purified metallic powder in a set of dies under extremely high pressure and then fusing the particles in an oven under controlled high temperature. This compression process compacts the powder metal until the part is approximately 90 percent the density of the solid metal or alloy. The density of the part can be controlled to an extent that the open pores in the powder-metal part, after fusion, may be impregnated with lubricants or filler resins and binders. The well-known sintered-bronze journal bearings with impregnated lubrication are prime examples of powder-metal technology.

Powder-metal parts may be made of aluminum alloys, copper alloys, steels, and stainless steels. Other metals and alloys also can be used in powder-metal processing.

The modern powder-metal part may be impregnated with resins and binders, which make possible the application of electroplated finishes such as copper, zinc, nickel, and chromium. If the part is made of one of the corrosion-resistant stainless steels, the plating process may be eliminated.

Parts may be produced using powder metal that normally would be difficult to machine. An example of powder-metal parts is shown in Fig. 12.25. Here are shown a group of metal parts, most of which would be difficult to make using other processes. The parts shown could be made using the investment casting process or machining techniques but would be costly and time-consuming to produce. Figure 12.26 is a closer view of the three small three-pointed parts that shows a minute hole in the center of the parts. Each division on the scale shown in Fig. 12.26 is equal to 0.020 in (1/50 inch). One of the parts shown in Fig. 12.26 had secondary machining operations performed on it (threading). All the parts shown in both figures are easy and economical to produce using powder-metal technology.

Design of powder-metal parts. The design and manufacturing of powder-metal parts are not difficult if the basic rules of powder-metal part design are followed and if the powder-metal part manufacturer is consulted during the design stages. The part manufacturer will advise you if the part can be produced as designed and what remedial

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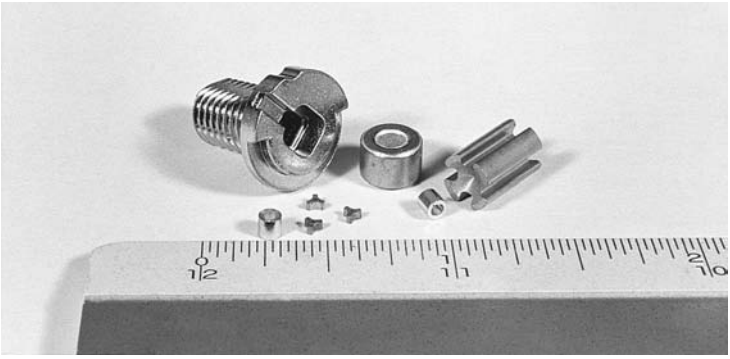

Figure 12.25 Samples of powder-metal parts.

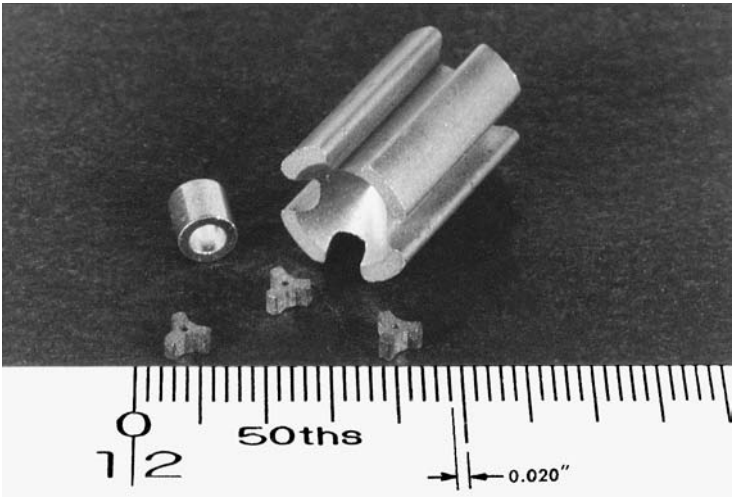

Figure 12.26 Close-up view of powder-metal parts. Note scale.

Typical Properties of Powder-Metal Parts

MATERIAL	CONDITION	DENSITY	ULTIMATE	YIELD	ELONGATION	IMPACT. FT-LBS.	HARDNESS
Low Alloy Steel	S/HT	6.8	110	110	<0.5	4.0	32HRC
Low Alloy Steel	S/HT	6.8	130	130	<0.5	6.0	34HRC
Stainless Steel	S	6.4	39	32	0.5	3.5	62HRB
Stainless Steel	S	6.5	60	39	10.0	28.0	62HRB
Stainless Steel	HT	6.5	105	105	<0.5	2.5	23HRC
Iron-Nickel	S	6.9	50	30	2.5	12	59HRB
Iron-Nickel	S/HT	7.0	135	135	<0.5	6.5	31HRC
Iron-Copper	S	6.7	50	45	<1.0	5.0	60HRB
Iron-Copper	S/HT	6.8	90	90	<0.5	4.5	35HRC

S = Sintered; HT = Heat-Treated; Density, g/cc; Ultimate strength = x1000 psi;; Yield = x 1000 psi; Elongation = %; Impact Unnotched Charpy, ft-lbs.; Hardness = Rockwell B or C scale, as indicated.

Figure 12.27 Typical properties of powder-metal parts.

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actions to take or design changes are needed to produce the part. The manufacturer also will advise you of the availability of the different metals and alloys for producing the part.

Basic rules for powder-metal part design

- Keep the outline elements of the part on lines parallel to the part axis or in the direction of compression of the male die.
- Do not design parts with reverse angles along the axis (the part cannot be extracted from the dies if this occurs).
- Keep wall sections or webs as thick as possible.
- Single tapered holes in the part are possible when the direction of taper allows extraction from the dies after compression of the powder metal.
- Limit the size or volume of the part to that which may be produced with available machinery.
- Do not specify electroplated finishes unless necessary (the part may be produced in a corrosion-resistant alloy if necessary).
- Holes in the part may be controlled to close tolerances.
- Check with the part manufacturer to ascertain if the part can sustain the imposed stress loads anticipated.
- The outline accuracy of parts can be closely controlled.

Some of the powder-metal part producers can provide design manuals or brochures to the design engineer that outline in more detail the design procedures for powder-metal parts.

Small-part design always should be reviewed to see if the design requirements can be met using powder-metal technology. Powder-metal technology is much further advanced today than in the past; then it was used mainly to produce journal bearings with impregnated lubrication.

12.7.1 Typical powder-metal parts and properties

Powder-metal technology has advanced greatly over the past 10 years. Although powder-metal parts have been in use for many years in the form of sintered bronze bearings, the technology now is able to produce parts with a drastic increase in compositions as well as strengths. Figure 12.27 (see previous page) shows some of the types

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Castings, Moldings, Extrusions, and Powder-Metal Technology

of materials now available through the powder-metal processes and their relative strengths for use in various types of parts.

Standards for powder metal parts are available from the Metal Powder Industries Federation (MPIF). MPIF Standard 35 lists the compositions and physical properties of available powder metals.

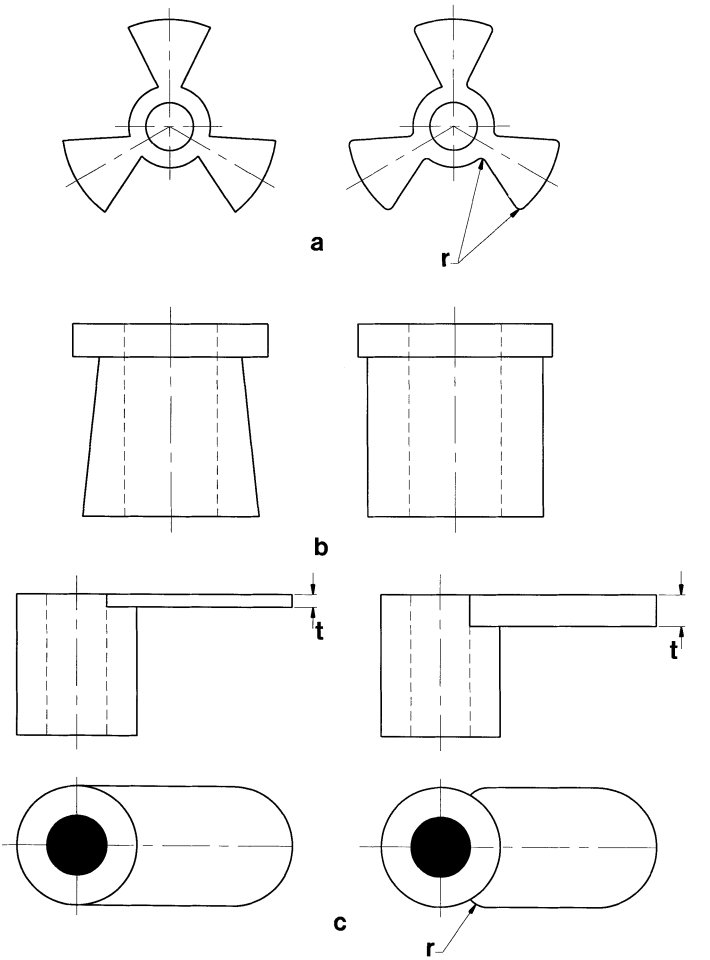

Figure 12.28 Typical powder-metal part design features. Parts shown on the left side are not acceptable; parts shown on the right side embody good design and are acceptable.

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For those interested in obtaining the full standards listings, the address of the MPIF is shown in Chap. 16.

The design of powder-metal parts is limited by the process used for compression of the different powder metals. Some examples of design considerations are shown in Fig. 12.28. The figures on the left are not recommended; the figures on the right are recommended. Notice that generous radiuses are required for powder-metal parts design. For more detailed information on the design of powder-metal parts, consult powder-metal manufacturers or the MPIF.

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Source: McGraw-Hill Machining and Metalworking Handbook

Chapter

13

Plating Practices and Finishes for Metal

Commercial products and equipment in all classifications require finishes of one type or other. These finishes range from basic oxide coatings to the various paints and plastics to electrodeposited metals such as copper, chromium, nickel, etc.

The finish or plating used on any particular part should contribute to the engineering qualities of the final product and not merely to its cosmetic appeal. The desired finish could include weather protection, resistance to corrosive chemicals, heat resistance, electrical conductivity, wear resistance, and improved lubrication qualities.

It is the design engineer's responsibility to specify the finish characteristics and specifications on a part or assembly. Designers should be aware of the types of finishes and plating processes that are available commercially and how to specify them on the design and detail part drawings. Arbitrary selection of a finish or plating and its thickness range can lead to many design problems relating to corrosion, cost, and dimensional interference.

This chapter will familiarize the designer, engineer, and other personnel in the metalworking industries with the common finishing processes, procedures for specifying thicknesses of platings, and the appropriate industrial standard specifications that control these finishes.

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13.1 Finishes

The finishing processes and methods in common use for engineering applications are as follows:

Mechanical finishing

- Sanding or grinding
- Brushing (scratch and satin)
- Sandblasting
- Shot peening and tumbling (metal or ceramic ball)
- Burnishing
- Mechanical powder plating
- Polishing

Chemical finishing

- Etching
- Bonderite
- Alodine
- Iridite
- Phosphatizing
- Passivating (stainless steels)
- Black oxide
- Blueing
- Teflon coating
- Other plastic coatings

Electrolytic oxides

- Sulfuric acid anodize (Alumilite, Alcoa process)
- Chromic acid anodize (aerospace and other applications), Martin hard-coat anodize (Martin-Marietta process)
- Electropolishing

Note: Anodizing may be performed on aluminum, magnesium, titanium, and zinc.

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Plating Practices and Finishes for Metal

Electroplating

- Copper plate
- Cadmium plate
- Chromium plate (bright, hard, and black)
- Nickel plate (bright, black, and chromium-nickel)
- Gold plate
- Silver plate
- Tin plate (tin-cadmium, tin-lead, and tin-nickel)
- Indium plate
- Rhodium plate
- Palladium plate
- Zinc plate (nickel-zinc, zinc with chromate)
- Lead plate

The base metals and their alloys that are commonly electroplated are iron, steel, stainless steel (more commonly passivated), aluminum, copper, brass, bronze, titanium, and magnesium.

Hot-dip plating

- Hot-dip tin
- Hot-dip zinc
- Hot-dip aluminum
- Hot-dip lead

13.2 Corrosion of Metals: Principles

The design engineer has four choices when planning for corrosion resistance of a metal part:

1. Use a corrosion-resistant alloy steel.
2. Use a nonferrous, noncorroding metal alloy.
3. Use plated steel or anodized alloys.

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4. Use a chemically coated, painted, or plastic-coated metal part (ferrous or nonferrous).

The third choice is usually the most economical, although it may not be the best choice. Plated-steel parts are the most common and suffice for most applications, although the choice of a more expensive alloy may be mandatory as a result of required antimagnetic properties, low electrical resistivity, restrictions on the weight of the part (such as in aerospace vehicles), and other considerations.

Basic principles of corrosion of metals and metallic alloys. All metals and alloys have a specific relative electrical potential. When metals of different electrical potentials, such as steel and copper, are in contact in the presence of moisture (electrolyte), a low-energy electric current flows from the metal having the higher potential to the one having the lower potential. This is called *galvanic action.* One result is that corrosion of the metal having the higher potential (steel in our example) is accelerated.

The mechanism is an anode reaction, a cathode reaction, the conduction of electrons through the metal from anode to cathode, and the conduction of ions through the electrolyte solution. Corrosion occurs in the anode area, whereas the cathode area is protected.

It is important to know from which of two metals current will flow. Figure 13.1 shows the galvanic or electromotive series for common engineering materials that gives potential differences (in volts) with respect to the hydrogen electrode. This chart will immediately show the difference in potential for these materials. The greater the potential difference, the greater is the galvanic action or the faster will the corrosion progress. By convention, the anode is considered positive and the cathode negative. Gold is the most noble metal, and magnesium one of the least noble metals.

If you study Fig. 13.1 closely, you will see why the different electrochemical batteries were derived. The potential differences between nickel, cadmium, zinc, iron, lead, and silver are such that electrochemical battery systems were able to evolve around these elements when used with the proper electrolytic solutions.

Corrosion has been estimated as causing over $125 billion in damages per year in the United States alone. Corrosion is at work 24 hours a day, 365 days a year and is a never-ending problem. Authorities on corrosion problems believe that much of this damage and loss can be prevented if design engineers pay closer attention to

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Plating Practices and Finishes for Metal

Galvanic/Electromotive Series - (for common engineering materials)

Engineering Material	Potential
Magnesium & magnesium alloys	-2.37v
Aluminum (1100 series)	-1.66
Zinc	-0.76
Chromium	-0.74
Type 304 stainless steel (active)	------
Type 316 stainless steel (active)	------
Steel, iron, cast iron	-0.41
Aluminum (2024)	------
Cadmium	-0.40
Nickel	-0.23
Tin	-0.14
Lead	-0.13
Copper	+0.34
Silver solder	------
Nickel (passive)	------
Chromium-iron (passive)	------
Type 304 & 316 Stainless steel (passive)	------
Silver	+0.80
Titanium	------
Platinum	+1.20
Gold	+1.50

Figure 13.1 Galvanic/electromotive series.

potential corrosion problems during the design process. Thinking about corrosion problems while selecting the design materials is the first step a product designer should undertake.

For example, the selection of high-strength steels to go into an environment containing sulfides or raw hydrogen is a grave design mistake. The high-strength steels will fail in these environments, although the authorities are not quite sure why this takes place, except that hydrogen embrittlement will occur (*Source:* J. Kruger, professor of materials science and engineering, Johns Hopkins University).

The use of dissimilar metals is another often-cited cause of corrosion problems. The welding of stainless steels that are not low in carbon content is another cause of stress-induced corrosion. Austenitic stainless steels with high nickel content and low carbon are recommended for welding applications (AISI 304, AISI 304L, AISI 316, and others).

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Plating Practices and Finishes for Metal

One of the best books for design engineers to use as a reference for corrosion problems is *Design and Corrosion Control,* by V. R. Pludek (Macmillan, 1977).

Electrochemical equivalents for various metals. The electrochemical equivalents and other related data for the various plating metals and alloys are shown in Fig. 13.2. If you study the data for chromium, you will see why this metal is a difficult metal to plate because it takes much electrical energy for thin coatings. Cadmium, on the other hand, is an easy metal to plate, but it is a toxic element, as are its salts.

Electroplating practice. The table in Fig. 13.3 lists the common plating metals and alloys and their possible baths, uses, and plating requirements. Procedures for actually performing different plating operations will be shown in a later section. Many of the plating processes and procedures are proprietary, their procedures being closely guarded trade secrets. Platings such as bright chromium, black chromium, gold, nickel-chromium, and others use proprietary procedures that are not published in any book. Plating has been called a "black art," and you will understand why when you try to obtain information on the exact processes and procedures used in some of the industrial plating practices. Plating procedures are difficult and must be controlled closely to exacting standards if the finished article is to be of high quality.

13.3 Electroplating Data and Specifications

13.3.1 Electroplating and oxide layer thickness ranges

Many plating thickness specifications call for plating thicknesses in micrometers (μm), but others may be specified in mils (0.001 in = 1 mil).

$$1\ \mu m = 0.00004\ in \text{ or } 0.04\ mils$$

$$25.4\ \mu m = 0.001\ in = 1\ mil$$

$$5\ \mu m = 0.0002\ in = 0.2\ mil$$

Both measurement units are given in the following listings, which summarize in outline form thickness specifications for various platings and coatings on a number of base-metal types.

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Electrochemical Equivalents and Related Data - Based on 100% Current Efficiency

Metal	mg/coulomb	gm/amp hr	oz/amp hr	Specific Gravity	oz/sq ft for 0.001 in	amp hr to deposit 0.001"/sq ft ♦	Symbol
Cadmium	0.58	2.10	0.074	8.64	0.72	9.73	Cd
Chromium	0.09	0.32	0.011	7.10	0.59	51.8	Cr
Copper	0.33	1.19	0.042	8.92	0.74	17.7	Cu
Gold	0.68	2.45	0.087	19.3	1.61	18.6	Au
Iron	0.29	1.04	0.037	7.90	0.66	17.9	Fe
Lead	1.07	3.87	0.136	11.3	0.94	6.91	Pb
Nickel	0.30	1.10	0.039	8.90	0.74	19.0	Ni
Palladium	0.28	0.10	0.035	12.0	0.10	28.6	Pd
Platinum	0.51	1.82	0.065	21.4	1.78	27.6	Pt
Rhodium	0.27	0.10	0.034	12.5	1.04	30.8	Rh
Silver	1.12	4.02	0.142	10.5	0.88	6.20	Ag
Tin	0.31	1.11	0.039	7.30	0.61	15.6	Sn
Zinc	0.34	1.22	0.43	7.10	0.59	13.7	Zn

NOTE: ♦ Equals specific gravity x 0.08323

Figure 13.2 Electrochemical equivalents and related data.

Electroplating Practice - Average operating conditions

Plating Metal	Typical Uses	Plating Solution Type	Plating Bath Temp. °F	Current Density Amps/ft^2	Volts DC	Throwing Power	Time to Deposit 0.001"
Cadmium	Protection	Cyanide	70-95	15-45	1-4	Good	20 min.
Chromium	Decorative, Engineering (Hard), Cylinder liners	Chromic acid	120	200-250	6-8	Poor	2 hours
Copper	Electroforming, Undercoat Stop-off for casehardening	Acid Cyanide Rochelle	75-120 75-100 140-160	15-40 5-15 20-60	1-2 1.5-3 2-3	Fair Good Good	35 min 90 min 45 min
Gold	Decorative, Electronics, PC boards	Cyanide Proprietary	120-160	5-15	2-6	Good	....
Indium	Bearing surfaces	Cyanide Sulfate Fluoborate	70-75 70-75 70-90	10-150 20 50-100	....	Good Poor Good	....
Iron	Electroforming, Repair	Chloride Sulfate	190 70-75	60 20	....	....	20 min 1 hour
Lead	Protection Bearing surfaces	Fluoborate	70-75	10-80	0.5	Good	40 min
Nickel	Protection, Decorative, Base coat for chromium	Sulfate-chloride Sulfamate Fluoborate	75-100	Varies	0.5-3	Fair	30 min
Rhodium	Decorative, Optical	Sulfate Phosphate	110-120	10-80	2.5-5	.....	.....
Silver	Protective, Decorative, Electrical contacts	Cyanide	80	5-15	1	Good	.....
Tin	Protective,	Sulfate	70-75	40	1-3	Fair	15 min

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	Food & dairy,	Fluoborate	75-100	50	.....	Good	10 min
	Bearings,	Stannate	150-190	40	4-8	Excellent	30 min
Zinc	Protective	Sulfate	75-100	15-400	.....	Fair	10 min
		Cyanide	100	10-50	.....	Good	40 min
			Alloys				
Brass	Rubber bonding, Decorative	Cyanide	75-100	3-10	2-3	Good	.....
Bronze	Decorative, Base for chromium, Stop-off for steel	Cyanide-stannate	155	20-100	3-6	Excellent	30 min
Lead-tin	Bearings Solderability, Electrotyping	Fluoborate	70-75	60	1-2	Good	.....
Tin-zinc	Solderability	Cyanide-stannate	150	10-75	4-5	Excellent	30 min
Tin-nickel	Printed circuits	Chloride-fluoride	150	25	1-2	Excellent	30 min

Figure 13.3 Electroplating practices table.

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13.3.2 Anodic coating thickness (anodized parts)

Aluminum

ASTM B 580-79

Type A hard coat	2.0 mil (50 μm)
B architectural	0.7 mil (18 μm)
D auto exterior	0.3 mil (8 μm)
E interior, a	0.2 mil (5 μm)
F interior, b	0.1 mil (3 μm)
G chromic acid	0.04 mil (1 μm)

Mil-A-8625C

Chromic acid	0.05–0.3 mil (1.3–8 μm)
Sulfuric acid	0.1–1.0 mil (3–30 μm)
Hard coat	0.5–4.5 mil (13–114 μm)

Magnesium

AMS 2478B

Acid, full coat	0.9–1.6 mil (23–41 μm)

Mil-M-45202C

Light HAE	0.1–0.3 mil (3–8 μm)
Heavy HAE	1.3–1.7 mil (33–43 μm)

13.3.3 Electroplating thicknesses and specifications

Cadmium plate

Range: 0.2–1.0 mil (5–25 μm)

Specification reference: ASTM A165-80

Note: Cadmium metal is toxic, as are its salts. Use may be restricted.

Chromium plate

Range: 0.01–6.0 mil (0.3–150 μm)

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Decorative: 0.01 mil (0.3 μm)

Engineering: 2 mil (50 μm)

Specify hard chrome on the drawing for corrosion resistance.

Heavy chrome plating (4–6 mil) range will have porosity.

Specification reference: Fed QQ-C-320B

Copper plate

Range: 0.1–5 mil (3–125 μm)

Specification reference: Mil-C-14550A

Used as a base for other platings

Gold plate

Range: 0.02–1.5 mil (0.5–38 μm) in eight thickness classes

Specification reference: Mil-G-45204B

Nickel plate

Range: 0.2–7.9 mil (5–200 μm) engineering coatings

Specification reference: ASTM B689-81 (may be soft or hard deposited within other specifications)

Nickel with chromium plate on steel

Range: 0.4–1.6 mil nickel; 0.01 mil chromium

Kinds of coatings include bright, dull, and layered.

Specification reference: ASTM B456-79

Also covers nickel with chromium on copper and copper alloys

Rhodium plate

Range: 0.008–0.25 mil (0.2–6.4 μm) engineering coatings

Specification reference: ASTM B634-78

Palladium plate

Range: 0.05–0.2 mil (1.3–5 μm)

Specification reference: ASTM B679-80

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Silver plate

Range: 0.04–1.6 mil (1–40 μm)

Types include mat finish, bright finish, tarnish resistant (chromate-treated)

Specification reference: ASTM B700-81

Note: Silver plating of electric current–carrying parts such as switch blades, breaker contacts, and other sliding parts is generally given as 0.2 mil (5 μm), except where industry specifications may call for 3 mil (76 μm). The 3-mil coating is more effective on surfaces subject to heavy friction, such as sliding electrical contacts.

Tin plate

Range: 0.2–1.2 mil (5–30 μm)

Specification reference: ASTM B545-72

Note: On electrical switch gear and other industrial equipment, 3-mil thickness is usually specified for service at paper mills and other environments where hydrogen sulfide in the atmosphere corrodes silver and other platings.

Zinc plating on steel

Range: 0.2–1 mil (5–25 μm) service conditions 1 through 4

The standard general thickness on most parts is 0.2 mil (0.0002 in). For severe service, the plating thickness should be 13 to 15 μm or 0.00057 in or ⁴⁄₁₀ mil (0.0006 in). Hot-dip coatings of 1 mil (0.001 in) are given to parts that are subject to extremely severe service.

Specification reference: ASTM B633-78

Note: Bright zinc plating on steel parts (usually sheet metal and machined parts) is often given a yellow chromate conversion coating after the zinc plate. This process imparts a gold, iridescent appearance. Many commercial parts are given this treatment for corrosion resistance in lieu of painting. Conversion coatings are also available for the following metals: silver, copper and its alloys, tin, aluminum, magnesium, zinc-base die-casting alloys, and electroplated chromium.

During the conversion process, a complex chromium metal gel forms on the part surface that contains hexavalent and trivalent chromium. When the soft gel coating dries, it becomes hard and

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Plating Practices and Finishes for Metal

somewhat abrasion-resistant. This then forms what is the preferred plating and coating for many engineering applications.

13.3.4 Plating metals: Characteristics and properties

Copper

Melting point: 1083°C (1981°F)

Specific gravity: 8.96 at 20°C

Reddish colored, malleable, and ductile metal. Excellent conductor of heat and electric current. Good corrosion resistance. Used as a plating base on irons and steels and for other plating metals such as chromium, tin, and nickel.

Cadmium

Melting point: 320.9°C (609.6°F)

Specific gravity: 8.65 at 20°C

Soft, bluish-white metal, similar to zinc in appearance. Cadmium is toxic, as are its compounds. Being replaced by zinc in many plating applications owing to its toxic nature. Used to plate mechanical fasteners, etc., but should not be specified unless required by special application.

Chromium

Melting point: 1890°C (3434°F)

Specific gravity: 7.19 at 20°C

Steel-gray, lustrous, and very hard metal. On a scale of 1 to 10, it would be 9, with only diamond at 10. Hexavalent chromium compounds are toxic. Excellent corrosion resistance for many applications. Attacked by hydrochloric acid, in which it dissolves. Heavily plated deposits become porous on the outer layers. Used to plate hand tools, surgical instruments, decorative trim, cutting tools and drills, and wear-resistant surfaces.

Nickel

Melting point: 1453°C (2647°F)

Specific gravity: 8.90 at 20°C

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Nickel is hard, malleable, ductile, slightly ferromagnetic, and a fair conductor of heat and electric current. Silvery-white metal that will take a high polish. Excellent corrosion resistance. Used to plate handguns, hand tools, decorative trim, and corrosion-resistant containers.

Gold

Melting point: 1063°C (1945°F)

Specific gravity: 19.32 at 20°C

Yellow, soft metal that is extremely malleable and ductile. Excellent conductor of heat and electric current. Excellent corrosion resistance. The metal alloys are measured in karats, 24 karat being pure gold. 18 karat = 18/24 = 0.75, or 75 percent pure gold; 14 karat = 14/24 = 0.583, or 58.3 percent pure gold, etc. Used to plate electrical contacts, printed circuits, watches, and other jewelry.

Silver

Melting point: 960.8°C (1761.4°F)

Specific gravity: 10.50 at 20°C

Brilliant white, lustrous metal. Harder than gold but still very malleable and ductile. Highest thermal and electrical conductivity of all metals. Stable in normal air but tarnishes when exposed to ozone, hydrogen sulfide, and air containing sulfur. Used to plate electrical contacts, conducting surfaces such as bus bars, eating utensils, and jewelry.

Silver was at one time used to plate printed circuit boards, but it exhibited a detrimental property known as *silver migration.* Thin whiskers of silver would form on printed circuit board conductor foil in the presence of an electric current and short out the circuits on the printed circuit board by bridging the spaces between the conductor patterns. This property of silver was not discovered until some time after the printed circuit boards were put into service on many military and commercial products. The result was many millions of dollars in damage, which could only be corrected by replacing all the defective printed circuit boards using gold- or tin-plated conductor foil.

Tin

Melting point: 231.9°C (449.4°F)

Specific gravity: (white tin) 7.31, (gray tin) 5.75 at 20°C

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Plating Practices and Finishes for Metal

Silvery-white metal that is malleable and slightly ductile. Resists seawater and tap water but is attacked by strong acids, alkalies, and acid salts. Used to plate electrical contacts, bus bars, and corrosion-resistant containers and tubing.

Indium

Melting point: 156.6°C (313.9°F)

Specific gravity: 7.31 at 20°C

Very soft, silvery-white metal. May be alloyed to produce very low melting point alloys. The metal is toxic.

Rhodium

Melting point: 1966°C (3570°F)

Specific gravity: 12.41 at 20°C

Silvery-white metal with low electrical resistance. Highly resistant to corrosion. Plated rhodium is extremely hard. The base metal is also ductile. Used to plate electrical contacts.

Palladium

Melting point: 1552°C (2825.6°F)

Specific gravity: 12.02 at 20°C

Steel-white metal that is soft and ductile when annealed. Very hard when cold worked. Does not tarnish in air. Uses include engineering plating and plating of electrical contacts.

Zinc

Melting point: 419.4°C (786.9°F)

Specific gravity: 7.13 at 20°C

Bluish-white lustrous, brittle metal. Fair conductor of electricity. Will burn in air at a red heat, producing clouds of white zinc oxide. Good corrosion resistance and used widely to plate irons and steels.

13.3.5 Summary of plating and finishing

Figure 13.4 lists most of the presently available and widely used plating processes and protective finishes, excluding paints and plastic coatings. These finishes have a wide range of uses in aerospace,

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Summary of Plating and Finishing Types and Applications

Finish	Application	Appearance
Brass	Used on high strength fasteners where a decorative finish is required	Gold iridescent
Cadmium	General purpose plating. High degree of corrosion resistance especially in salt atmospheres. Soft finish not for threaded applications requiring frequent tightening cycles. Cadmium is toxic. Zinc recommended as replacement.	Silver-gray
Cadmium and clear chromate	Suited for applications for hand contact. Corrosion resistant	Clear
Cadmium and black chromate	Recommended where black color is desired. Note: chromate can be applied in red, green, blue or other color as suits the application.	Black or color
Cadmium and bronze chromate	Normally used in military applications for identification of plating type.	Gold iridescent
Cadmium and yellow iridescent chromate	Similar to bronze	Yellow iridescent
Cadmium and olive drab chromate	Good for paint bonding applications.	Dull olive
Cadmium and phosphate	Similar to cadmium and olive drab chromate	Black
Copper	Used on Allen threaded products. Also for high heat applications.	Copper-matte
Chromium, decorative	Decorative and corrosion applications. Plating is usually very thin.	Bright or satin
Chromium, hard	A most durable plating which is extremely hard. Expensive. Engineering aplications. Cutting tools and drills.	Satin
Lead	For soldering applications.	Matte
Nickel	Decorative appearance, excellent wear and corrosion resistance.	Matte or bright
Silver	Electrical properties, utensiles, appearance.	Matte or bright
Tin	Anti-seize properties, corrosion resistance, non-toxic.	Grayish-white
Zinc	Popular plating for many applications; hardware, steel sheets, machined parts.	Bluish-white
Zinc and clear chromate	Similar to cadmium and clear chromate. Corrosion resistance, economical.	Clear
Zinc and black chromate	Similar to cadmium and black chromate. Where black color is desired.	Black

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Zinc and bronze chromate	Similar to cadmium and bronze chromate. Color applications.	Gold iridescent
Zinc and yellow iridescent chromate	Similar to cadmium and yellow iridescent chromate. Color applications. Popular engineering finish. Economical and attractive for industrial applications.	
Zinc and olive drab chromate	Similar to cadmium and olive drab chromate. Good paint adhesion properties.	Dull olive
Zinc and phosphate	Similar to cadmium and phosphate. Black for color applications.	Black
Anodic	Finishes for aluminum, magnesium, and titanium. Many types and thicknesses available.	Many colors
Black oxide	For threaded fasteners such as set-screws. Only mildly corrosion and rust resistant. Normally applied to irons and steels. Often oiled.	Black
Iron phosphate	For hardware which is severely handled. Decorative gray finish.	Oily gray-black (oil finish)
Manganese phosphate	For thread lubrication applications. For frictional contact applications. Supplied oiled or waxed for additional protection	Gray-black (oil finish)
Black nitrate	For stainless steel fasteners which require uniform black finish.	Dull or luster black
Passivation	For stainless steel fasteners and parts to prevent corrosion. Acid treatment.	Bright or matte
Zinc phosphate	For exposed fasteners requiring good paint adhesion properties. Dry or lubricated.	Dull gray (oil coating)
Teflon coating	Corrosion resistant and high lubricity. For non-galling anti-seizing applications. Used for bearings. New processes incorporate anodizing with teflon impregnation.	Gray to black

Figure 13.4 Summary of plating and finishing.

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commercial aircraft, automobiles, consumer products, and other industrial applications. The name of the finish, its applications, and its final appearance are all listed in the figure. For further information concerning the latest military specifications and American standard specifications for these finishes, consult the plating companies or finishers.

The effective corrosion resistance of selective platings and finishes is shown in Fig. 13.5. The thicknesses or ranges are shown in inches. As can be seen from the data in the figure, hard chromium is one of the best engineering finishes for metal products, although it is expensive compared with the other common platings.

13.4 Plating Baths and Procedures

This section discusses the chemical compositions of various plating baths and the plating voltages, current densities, and other requirements for plating the following metals:

- Cadmium
- Chromium (bright, decorative, and hard, for engineering applications)
- Copper
- Gold
- Nickel
- Rhodium
- Silver
- Tin
- Zinc
- Woods nickel strike
- Silver strike

13.4.1 Cadmium plating

Figure 13.6 shows the composition of the bath and operating conditions for cadmium plating. Cadmium metal has a toxic effect that is similar to that of mercury. Mercury is highly toxic and has contributed to a large extent to pollution of the environment, especially

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Effective Corrosion Resistance of Selective Platings - Minimum thicknesses are given in inches

Plating or Surface Treatment	Specification	Type	Class	Minimum Thickness	Salt Spray Test (minimum hours)	
					White Corrosion	Rust
Anodize	Mil-C-5541A	.....	.....	.....	168	.....
	Mil-A-8625B	I, II	.....	.....	240	.....
Cadmium and Chromate	AMS-2400L1	.....	.....	0.0002-0.0003	100	.....
	AMS-2400L2	.....	.....	0.0002-0.0004	100	.....
	AMS-2400L3	.....	.....	0.0003-0.0005	150	.....
Cadmium and Chromate	QQ-P-416a	II	1	0.0005	96	.....
	QQ-P-416a	II	2	0.0003	96	.....
	QQ-P-416a	II	3	0.0002	96	.....
	Mil-C-8837	II	1	0.0005	96	.....
	Mil-C-8837	II	2	0.0003	96	.....
	Mil-C-8837	II	3	0.0002	96	.....
Chromium, hard	Mil-C-11436	.....	.....	0.0012	.....	100
Lead	Mil-L-13808	I, II	3	0.00025	.....	24
	Mil-L-13808	I, II	2	0.0005	.....	48
Manganese Phosphate, dry	Mil-P-16232C	M	3	0.0002	.....	1.5
Manganese Phosphate, oil	Mil-P-16232C	M	2	0.0002	.....	24
Tin	Mil-T-10727A	I	.....	0.0002	.....	24
Zinc	Mil-Z-325a	I	2	0.0005	.....	96
	Mil-Z-325a	I	3	0.0002	.....	36
Zinc Phosphate, dry	Mil-P-16232C	Z	3	0.0002	.....	2
	Mil-P-16232C	Z	2	0.0002	.....	48
Zinc and Chromate	QQ-Z-325a	II	2	0.0005	96	.....
	AMS-2402E	.....	.....	0.0002-0.0003	100	.....
	QQ-Z-325a	II	3	0.0002	96	.....
	AMS-2402E	.....	.....	0.0003-0.0005	150	.....
Zinc and Phosphate	QQ-Z-325a	III	2	0.0005	.....	96
	QQ-Z-325a	III	3	0.0002	.....	36

Figure 13.5 Corrosion resistance of platings.

Plating Practices and Finishes for Metal

Plating Bath Composition and Operating Conditions for Cadmium

Composition	g/L	oz/gal
Cadmium fluoborate	240.0	32.2
Fluoboric acid		to pH, (see pH below)
Boric acid	22.5	3.0
Ammonium fluoborate	60.0	8.0
Licorice	1.0	0.134
Cadmium present	95.0	12.6
pH, calorimetric		3.0-3.5
Conditions:		
Temperature		70-100°F (20-38°C)
Current density		30-60 amp/ft^2 (3-6 amp/dm^2)
Agitation, cathode		Preferred
Cathode efficiency, %		100
Ratio of anode to cathode area		2:1
Anode material		Cadmium
Volts		4-6
(barrel)		6-12
Filtration: as required		

Uses: Rust preventive coating
Application: Over all ferrous base metals. Freedom from hydrogen embrittlement.
Note: Excess free acid can reduce efficiency and cause hydrogen embrittlement. Contamination with copper, lead or zinc can effect color and corrosion resistance of the deposited plating.

Figure 13.6 Cadmium plating.

in the water systems worldwide, where mercurous and cadmium solutions are disposed of on a regular basis. Zinc plating should be used to replace cadmium-plated parts, except where the specifications limit the choice to cadmium. The fumes that result when cadmium is used are toxic, as are those of mercury. Grave physical damage is caused by the ingestion of either metal (elements).

Note: The key numbers for the materials of construction for cadmium plating include 3, 8, 12, 13, and 14. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.2 Copper plating

Figure 13.7 shows the composition of the bath and operating conditions for one of the popular and easy-to-use methods of applying

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Plating Practices and Finishes for Metal

Plating Bath Composition and Operating Conditions for Copper

Composition	g/L	oz/gal
Copper sulfate	200-250	28-34
Sulfuric acid	30-75	4-10
Copper content	40-50	5.2-6.6
Sulfuric acid	30-75	4-10
Conditions:		
Temperature:		70-120°F (21-49°C)
Current density:		20-100 amp/ft^2 (2-10 amp/dm^2)
Agitation:		Preferred
Cathode efficiency, %		95-100
Ratio of anode to cathode area		1:1
Anode material		Copper
Volts		> 6 or higher for some applications

Filtration: continuous, especially for heavy coatings.

Uses: Heavy copper deposits to any required thickness.
Application: To all ferrous metals over copper strike. Under nickel and chromium deposits for protective coatings. For electroforming-electrotypes, printing rolls for textiles and rotogravure and other applications.
Note: check the acid content for most problems.

Figure 13.7 Copper plating

copper plating to base metals. Both copper and nickel are used for *strikes,* which are required before a plating metal is applied to a base metal such as iron or steel and other metals. Copper plating is applied most frequently over irons and steels prior to the final plating, which may be cadmium, nickel, chromium, tin, or another metal. Copper sulfate is poisonous and also is used to pressure-treat lumber and to provide a fungus-resistant coating to many articles, as well as a great variety of other commercial applications.

Note: The key numbers for the materials of construction for copper plating include 5, 8, 13, 14, and 15. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.3 Chromium plating

Figure 13.8 shows the composition of the bath and operating conditions for chromium plating. Chromium plating may be applied directly over steel tools when proper procedures are followed. This application of chromium plating had been used to coat cutting tools and drills. The present technology coats cutting tools and drills with titanium nitride and titanium carbide, which are harder and

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Plating Practices and Finishes for Metal

Plating Bath Composition and Operating Conditions for Chromium

Composition	g/L	oz/gal
Chromic acid	398	53.0
Sulfuric acid (concentrated)	4.0	0.53
Ratio CrO_3/H_2SO_4	100:1	

Conditions:	
Temperature:	110-120°F (43-49°C)
Current density	0.7-1.5 amp/in² (10-22 amp/dm²)Cathode efficiency, %
	13-18
Anode material	Pure lead
Ratio of anode to cathode area	2:1 or more (variable)
Volts	6-12

Agitation: Not normally used.
Filtration: Uncommon.
Note: Trivalent chromium is usually required for normal operation of the bath (about 1% of the chromic acid content)

Uses: Bright decorative deposits 0.01 to 0.03 mil. Hard deposits are 0.1 mil and heavier.
Applications: Decorative coating over copper and/or nickel protective coatings on all base metals. Industrial or hard coating over ferrous base metals for tools and dies, cutting tools and drills. Piston rings and cylinder liners.
Note: Problems ocurr with improper trivalent chromium levels, contamination with iron, copper or nickel. Avoid contamination or problems will ocurr. Current densities must be maintained because of the poor throwing power of chromium plating baths.

Figure 13.8 Chromium plating.

more wear resistant than chromium. Chromium is a very hard metal with the hardness of sapphire, but the newer titanium coatings are found more often on modern cutting tools and drills. Chromium plating enhances the appearance and corrosion resistance of many articles, but by modern standards it is considered an expensive electroplating process. Many applications still require chromium plate when the engineering specifications so direct. Chromium plating is difficult owing to the high current densities required and the poor "throwing" power of chromium. The shape and area of the anode in chrome plating are important, as is its position relative to the cathode or article being plated.

Note: The key numbers for the materials of construction for chromium plating include 1, 5, 9, 10, 14, and 15. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.4 Gold plating

Figure 13.9 shows the composition of the baths and operating conditions for two types of gold plating. Gold plating has many industrial

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Plating Practices and Finishes for Metal

Plating Bath Composition and Operating Conditions for Gold

Composition	Matte		Bright	
	g/L	oz/gal	g/L	oz/gal
Gold as cyanide	2-12	0.25-1.5	4-16	0.5-2
Potassium cyanide	15-45	2-6	15-90	2-12
Potassium carbonate	0-45	0-6	0-30	0-4
Potassium phosphate	0-45	0-6	0-45	0-6
Potassium hydroxide	10-30	1.3-4	10-30	1.3-4
Brighteners	0	0	0.1-10	0.01-1
Conditions:				
Temperature:	120-160°F (50-70°C)		60-75°F (15-25°C)	
pH:	11-13		9-13	
Current density	1-5 amp/ft^2 (0.1-0.5 amp/dm^2)		3-15 amp/ft^2 (0.3-1.5 amp/dm^2)	
Agitation	Moderate		Rapid	
Anodes	Platinum, stainless steel, gold			

Uses: Plating for corrosion prevention and electrical conductivity. Decorative.
Applications: Jewelry, printed circuit boards, integrated circuits, electrical contacts, relays.
Note: Problems with contamination. Gold solution baths are extremely sensitive to contamination, either organic or metallic. Nickel is used as the barrier or base layer (see nickel strike baths, Figure 13-10).

Figure 13.9 Gold plating.

applications, including printed circuits, high-quality relay points, integrated-circuit applications, and general electrical contact plating, where a high-conductivity, corrosion-resistant coating is required. The applications in jewelry are numerous but are not detailed in this section.

Note: The key numbers for the materials of construction for gold plating include 3, 9, and 14. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.5 Nickel plating

Nickel is a lustrous, highly corrosion-resistant metal with countless applications in industry. The metal is used in alloying steels and beryllium-copper (beryllium-nickel) alloys, as well as in the construction of nickel-cadmium electrochemical cells for batteries. Figure 13.10 shows the composition of the baths and operating conditions for three types of nickel plating. Nickel plating is used in *nickel strikes* as a preplating deposit applied subsequent to the plating of other metals. A popular nickel strike called *Woods nickel strike* is shown in Fig. 13.15.

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Plating Practices and Finishes for Metal

Plating Bath Composition and Operating Conditions for Nickel - Also nickel strikes.

Composition	Watts Type g/L	Watts Type oz/gal	High Chloride g/L	High Chloride oz/gal	All Chloride g/L	All Chloride oz/gal
Nickel sulfate	300	40	240	32	.....	.....
Nickel chloride	45	6	90	12	240	32
Boric acid	30-38	4-5	30-38	4-5	30	4
Nickel content	77.0	10.3	75	10	75	10
pH range (electrometric)	2.0-2.5		2.0-2.5		0.9-1.1	
Hydrogen peroxide to give free oxygen, ppm (Engineering applications)	5-10		5-10		5-10	
Conditions:						
Temperature:	130°F (55°C)		130°F (55°C)		130°F (55°C)	
Current density:	10-60 amp/ft^2 (1-6 amp/dm^2)		10-60 amp/ft^2 (1-6 amp/dm^2)		50-100 amp/ft^2	
Agitation:	Cathode					
Ratio of anode to cathode	1:1		1:1		1:1	
Filtration:	Continuous					
Volts:	6-12		6-12		6-12	
Anode material	Nickel, bagged, cast or rolled, depolarized or carbon type.					

Uses: Bath 1 and 2 (dull nickel 0.1-2.0 mil). For bright nickel proprietary brighteners are required. Bath 3 for hard, dull nickel, any thickness.
Applications: For decorative and protective coatings, copper and/or nickel-chromium, on most base metals use baths 1 or 2. For a nickel strike, especially over steel, copper and copper alloys prior to silver palting, use baths 1 or 3 (sometimes less concentrated).

Figure 13.10 Nickel plating.

Note: The key numbers for the materials of construction for nickel plating include 3, 4, 5, 8, 13, 14, and 15. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.6 Rhodium plating

Figure 13.11 shows the composition of the baths and operating conditions for three types of rhodium plating. Rhodium is a highly corrosion-resistant metal with a high luster used in special corrosion-resistant applications. See preceding sections for a description of this metal and its various applications.

Note: The key numbers for the materials of construction for rhodium plating include 8, 9,12,13, and 14. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.7 Silver plating

Figure 13.12 shows the composition of the baths and operating conditions for two types of silver plating. Silver plating should receive

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Plating Bath Composition and Operating Conditions for Rhodium

Composition	Bath 1 g/L	Bath 2 g/L	Bath 3 g/L
Rhodium metal ♦	2	2	10-20
Sulfuric acid, pure, % vol	2.0	.....	2.5
Phosphoric acid, 85%, % vol	.....	2.0	.....
Conditions:			
Temperature:	104-113°F	104-113°F	122°F
Current density:	10-100 amp/ft^2	10-100 amp/ft^2	10-20 amp/ft^2
Agitation:	As required for all baths		
Cathode efficiency:	80%	80%	85%
Ratio of area anode to cathode:	1:1	1:1	1:1
Anode material:	Platinum for all baths		
Volts:	6	6	6

Note: nickel undercoat required, except for gold and platinum group.
Uses: Thin, bright decorative and corrosion resistant coating applications.
Decorative thickness: 0.001-0.006 mil; Scratch and corrosion resistance: 0.06 to over 1.0 mils.

Note: ♦ Metal is added in form of concentrate, as required.

Figure 13.11 Rhodium plating.

Plating Bath Composition and Operating Conditions for Silver

Composition	Bath 1		Bath 2	
	g/L	oz/gal	g/L	oz/gal
Silver cyanide	36	4.8	105	14.0
Cyanide potassium	60	8.0	113	15.0
Carbonate, potassium	45	6.0	15-115	2-15
Potassium hydroxide	.....	.....	30	4.0
Carbon disulfide	0.00075	0.0001		
Silver content	28.7	3.5 (Troy)	84	10.2 (Troy)
Free potassium cyanide	43	5.7	62	8.2
Conditions:				
Temperature	75-90°F (24-32°C)		110-130°F (43-55°C)	
Current density	5-15 amp/ft^2 (0.5-1.5 amp/dm^2)		60-150 amp/ft^2 (6-15 amp/dm^2)	
Agitation	Cathode		Cathode and solution	
Cathode efficiency	100%		100%	
Ratio of anode to cathode area	1:1		2:1-4:1	
Anode material	Silver		Silver	
Volts	< 6		< 6	
Filtration	As required		Continuous through paper	

Uses: Bath 1 for bright silver deposits following silver strike, 0.1-1.3 mil. Bath 2 for heavy silver deposits after silver strike, up to 60 mil.
Applications: Bath 1 decorative and protective. Bath 2 for engineering applications
Problems: Avoid problems by closely controlling current densities, cleanliness of solution and prestrike quality. Avoid organic contamination. Proprietary solutions for full bright processing are available from the plating suppliers.

Figure 13.12 Silver plating.

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a *silver strike* prior to the finished plating being applied. Silver strike plating solutions are shown in Fig. 13.16.

Note: The key numbers for the materials of construction for silver plating include 1, 2, 3, 9, 10, 13, and 14. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.8 Tin plating

Figure 13.13 shows the composition of the baths and operating conditions for three types of tin plating. Tin plating has many applications in industry, including corrosion-resistant finishes, electrical conductivity, and solderability.

Note: The key numbers for the materials of construction for tin plating include 1, 2, 3, 13, and 14. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.9 Zinc plating

Figure 13.14 shows the composition of the baths and operating conditions for two types of zinc plating for rack and barrel applications.

Plating Bath Composition and Operating Conditions for Tin

Composition	Bath 1		Bath 2		Bath 3	
	g/L	oz/gal	g/L	oz/gal	g/L	oz/gal
Sodium stannate	90	12	80	10.6	140	19
Sodium hydroxide	7.5	1	.....	.....	15	2
Potassium hydroxide	.....	.....	30	4.0	.....	.....
Hydrogen peroxide, 100 vol	As required (0.07)					
Tin content	38	5.0	29	3.8	60	8.0
Conditions:						
Temperature	140°F (60°C)		185°F (85°C)		200°F (95°C)	
Current density	10-25 amp/ft^2 (1-2.5 a/dm^2)		40 amp/ft^2 (4 amp/dm^2)		55 amp/ft^2 (5.5 amp/dm^2)	
Agitation, cathode & solution	Optional		Prefered		Not required	
Cathode efficiency	60-90%		80-100%		90%	
Ratio of anode to cathode area	1:1		1:1		1:1	
Anode material	Tin		Tin		Tin	
Filtration:	As required.....					
Volts	6		6		6	

Uses: Average tin coating thickness 0.03-0.3 mil. For protective coatings 1.0-3.0 mil.
Applications: Baths 2 and 3 are ffor electro tin plate. Bath 1 is used for plating all base metals for ease of soldering, protective coatings or good throwing power.

Figure 13.13 Tin plating.

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Plating Practices and Finishes for Metal

Plating Bath Composition and Operating Conditions for Zinc

Composition	Rack		Barrel	
	g/L	oz/gal	g/L	oz/gal
Ammoniated Solutions:				
Zinc chloride	75-95	10-12.5	35-65	4.5-8.5
Ammonium chloride	90-120	12-16	112-225	15-30
Sodium chloride	45-68	6-9	.....	.....
Boric acid or ammonium acetate	19-26	2.5-3.5	19-26	2.5-3.5
pH	4.4-5.6		4.4-5.6	
Temperature	60-110°F (15-45°C)		60-110°F (15-45°C)	
Conditions: Anode material	High purity zinc. Anode current density: 5-30 amp/ft^2			
Cathode current density	2-60 amp/ft^2			
Potassium solutions:				
Zinc chloride	75-85	10-11.3	50-85	6.7-11.3
Potassium chloride	200-270	27-36	180-270	24-36
Boric acid or Potassium acetate	7.5-12	1.0-1.6	7.5-12	1.0-1.6
pH	4.4-5.6		4.4-5.6	
Temperature	60-110°F (15-45°C)		60-110°F (15-45°C)	
Conditions:	Same as above baths			

Uses and applications: General corrosion resistant coating 0.2 to 3.0 mils for irons and steels. Bright zinc produced with these solutions. A yellow chromate coating is often applied over the deposited zinc plate.

Figure 13.14 Zinc plating.

Zinc is the most widely used of all plating metals because of its good corrosion resistance, quick and easy application, and low cost.

Note: The key number for the materials of construction for zinc plating is 14 [linings of polyvinyl chloride (PVC) or polypropylene].

13.4.10 Woods nickel strike solution

Figure 13.15 shows the composition of the striking bath and operating conditions for Woods nickel strike. This nickel strike can be applied on many base metals prior to other plating operations.

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Plating Bath Composition and Operating Conditions - Woods nickel strike

Composition	g/L	oz/gal
Nickel chloride	180	24
Hydrochloric acid (commercial)	10 to 12% by volume.....	
Conditions:		
Temperature	100°F (35°C)	
Current density	20-100 amp/ft^2 (2-10 amp/dm^2)	
Anodes	Nickel	

Uses and applications: This is a widely used strike which is effective on stainless steels, nickel, high-alloy steels and carburized and hardened steels. Time of strike: 30 seconds to 2 minutes. Nickel content will climb in this bath and should be maintained at 45-60 g/L (6-8 oz/gal), by decanting part of the solution and replacing it with hydrochloric acid.

Figure 13.15 Woods nickel strike.

Note: The key numbers for the materials of construction for Woods nickel strike include 3, 4, 8, 12, 13, 14, and 15. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.11 Silver strike solutions

Figure 13.16 shows the composition of the baths and operating conditions for three silver strike solutions. These strikes should be applied prior to the finished silver plating processes shown in Fig. 13.12.

Note: The key numbers for the materials of construction for silver strikes include the following: For baths 1 and 2, use 1, 2, 3, 9, 10, 13, and 14; for bath 3, use 8, 9, 10, 12, 13, 14, and 15. See Fig. 13.17, which shows the key numbers and the respective materials.

13.4.12 Materials of construction for electroplating processes

Figure 13.17 presents the materials of construction for the previously listed plating processes. The key numbers are referenced to the respective applicable materials.

Precautionary note: The materials and chemicals used in the electroplating processes are almost all toxic to some extent, with some of the compounds being extremely poisonous (such as the cyanides). Extreme caution should be followed when handling these materials and chemicals. Also, some of the fumes created in the plating processes are also toxic to a high degree. The proper equipment and

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Plating Bath Composition and Operating Conditions for Silver Striking

Composition	Bath 1		Bath 2		Bath 3	
	g/L	oz/gal	g/L	oz/gal	g/L	oz/gal
Silver cyanide	1.7	0.23	7	0.9	.....	.....
Potassium cyanide	75	10	75	10		
Copper cyanide	15	2	.....	.....	.....	.....
Nickel chloride	.....	.....	.....	.....	240	32
Hydrochloric acid Specific gravity 1.18					10.0%/volume	
Silver content	1.6	0.2	6	0.7		
Copper	10.5	1.4	.....	.....	.....	.....
Nickel	.....	.....	.....	.....	60	8
Free cyanide, KCN	53	7	71	9.5	.....	.....
Conditions:						
Temperature	75°F (24°C)		75°F (24°C)		75°F (24°C)	
Current density	30 amp/ft^2 (3 amp/dm^2)		30 amp/ft^2 (3 amp/dm^2)		150 amp/ft^2 (15 amp/dm^2)	
Time	0.33 min.		1 min		1-2 min	
Anode material	Steel		Steel		Nickel, bagged	
Volts	< 6		< 6		6	
Filtration	As required		As required		Constant	

Uses: Bath 1, first strike on steel; bath 2, second strike on steel or silver strike over nickel or other base metal; bath 3, first strike on steel or other base metal.
Applications: Strikes 1, 2 and 3 for regular silver plating. Strike 3 for engineering applications.

Figure 13.16 Silver strike.

ventilation must be used with the electroplating processes. As an example, the fumes from the chromium plating processes that use chromic acid are not only toxic but also corrosive. Any plating process that uses the cyanide compounds should be watched closely and handled with extreme caution, paying particular attention to proper venting of the fumes.

Because of the very high current densities used with some of the plating processes, the electrodes (anode and cathode) must be guarded against short-circuits. The operating voltages are low, but the power involved can be very high owing to the large electric currents required in certain processes (chromium plating).

13.5 Coloring Processes for Metals, Alloys, and Phosphating Steels

This section lists some of the coloring processes used to color metals and alloys. Coloring of metals may be for appearance as well as for additional protection against corrosion and rusting. These processes have evolved over a span of many years and are used widely in the

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Materials of Construction for Plating Applications

Key	Material	Uses
1	Steel, low carbon	Tanks, filters, pumps, pipe, fittings and heating coils
2	Cast iron	Pumps, filters, valves and fittings
3	Stainless steel (316)	Tanks, pumps and filters
4	High silicon cast iron	Pumps, pipe, fittings and heat exchangers
5	Lead (6% antimony alloy)	Tank linings, pipe
6	Copper	Heating coils
7	Nickel	Heating coils
8	Carbon (Karbate)	Heaters and heat exchangers, pumps and air diffusers
9	Glass (Pyrex or tempered)	Tanks, heat exchangers and pumps
10	Chemical stoneware	Tanks, tower concentrators and tower packing
11	"Haveg"	Tanks and pipes
12	Hard rubber	Pipe, fittings and pumps
13	Rubber (Approved types)	Tank linings and hose
14	Plastics (Approved types)	Tank linings, hose, pipe, fittings, barrels, heating coils
15	Acid resistant brick	Tank linings
16	Wood	Tanks

Note: Plastic tanks or liners can influence the current distribution patterns within the plating tanks. Tests must be run to determine the proper plastic for each particular application. Polyurethane, polyethylene, polystyrene, polypropylene, ABS (Acrylonitrile-Butadene-Styrene), acetals, acrylics, nylons and polyvinyl chlorides may be usable for many applications.

Figure 13.17 Materials of construction for plating applications.

metal finishing industries. Most of the processes involve the use of chemical action together with the application of heat.

It should be noted that the finished appearance of the metal being colored is affected to a great extent by how well the bare metal itself is finished and polished. For example, in the blueing process for handguns and rifles, the base metal is finished very carefully and is highly polished prior to blueing. If the metal parts are not finished and highly polished, the blueing process will not hide the defects in the base metal.

13.5.1 Coloring metals (ferrous and nonferrous)

Black oxide. Irons and steels may be given a black finish or black oxide finish by either of two processes:

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1. Heat the ferrous metal part to approximately 500 to 700°F, and plunge it into a container of good-quality machine oil. Reheat and plunge the part into the oil a number of times until the desired depth of black is obtained. Use precautions on hardened and tempered parts.
2. A thin black oxide coating also may be applied to iron and steel parts by immersing the parts in a boiling solution of sodium hydroxide and mixtures of nitrates and nitrites (sodium nitrate, potassium nitrate, etc.).

Blueing irons and steels. Many ferrous metal parts receive a blueing operation to enhance their appearance and also as a rust-preventive coating. Handguns, rifles, and shotguns normally receive a blueing operation unless chromium or satin nickel is specified. The following blueing process imparts a fine blue to blue-black finish: Clean the metal with a potassium bichromate–sulfuric acid solution, and then wash with ammonium hydroxide solution and wipe dry with a clean, lint-free cloth. Apply ammonium polysulfide until the desired depth of blueing is obtained. The finish may be made nearly black by repeating the process of applying the ammonium polysulfide. A light machine oil or silicone cloth wipe then will provide the surface with excellent corrosion and rust resistance.

Phosphating irons and steels. Three types of phosphate coatings (conversion coatings) are given to ferrous metals: zinc phosphate, iron phosphate, and manganese phosphate. Zinc phosphate coatings vary in color from light to dark gray; iron phosphate, dark gray; and manganese phosphate, dark gray, becoming black with service. The phosphate coatings are used for paint bases, for an aid in cold working the metal, and for rust prevention.

The phosphatizing solution contains approximately 3% to 5% phosphoric acid by volume. The part to be phosphatized is first thoroughly chemically cleaned and dipped into a solution of 2% by volume hydrochloric acid for approximately 15 seconds and then water rinsed and dried. The part is then immersed in the phosphatizing bath for the time required to impart the desired coating. Zinc plates and zinc parts are also phosphatized in the same manner. Stainless steels and certain alloy steels cannot be phosphatized.

Passivation of copper and copper alloys. A passivation coating may be applied to copper and its alloys that imparts a blue-green color or patina. This coating is corrosion resistant. The passivation solution may be made using the following solution composition:

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1. 6 lb ammonium sulfate
2. 3 oz copper sulfate
3. 1.4 fluid oz technical ammonia (specific gravity = 0.09)
4. 6.5 gal water

Apply the solution with a spray to the chemically cleaned copper or copper alloy parts in six applications, drying between applications. The patina appears after approximately 6 hours and continues as the part weathers.

Copper and copper alloy blackening (alloys with more than 85 percent copper). To color copper and its alloys black, use the following procedure: Make a solution consisting of 4 oz arsenious oxide, 8 fluid oz hydrochloric acid (specific gravity = 1.16), and 1 gal water. Then

1. Heat the solution to 175 to 200°F.
2. Immerse the copper or copper alloy parts until a uniform black color is obtained.
3. Brush the parts while wet, dry the parts, and apply a protective clear finish such as polyurethane varnish.

Coloring brasses. Brass may be given a green color with the following procedure: Mix a solution containing 1 oz ferric nitrate, 6 oz sodium thiosulfate, and 1 gal water. Then

1. Heat the solution to 160 to 180°F.
2. Immerse the brass parts in the solution until the desired color is obtained.
3. Dry and coat with a clear protective finish such as clear lacquer or polyurethane varnish.

13.6 Metal Finishing, Phosphating, and Cleaning Solutions and Formulas

The following solutions and formulas for cleaning and finishing metals are for use by metal fabricating facilities for mechanisms and small, moving detail parts generated mainly for use in mechanisms and other ferrous metal products. These solutions, formulas, and

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finishing processes should be used on all ferrous metal parts where a zinc, zinc and yellow chromate, or other electroplated finish is neither desired nor required. Zinc-plated and chromated parts and other parts that are electroplated usually increase in size owing to the thickness of the electroplated deposit. A study should be made, and the recommended parts that do not require a zinc, zinc and yellow chromate, or other electroplated finish should be phosphated in lieu of electroplating.

Phosphated metals (most ferrous metals and ferrous alloys) do not gain a significant plated thickness to interfere with mating parts on close assembly work. The simple phosphate coatings (which use only phosphoric acid and water as a 2% to 4% solution) are normally only 1.5 to 2.0 μin thick. Many industrial parts and products may receive a metallic phosphate finish in lieu of a zinc and yellow chromate or other electroplated finish, which may be expensive and require the services of outside vendors (platers). Since the phosphated finishes are not electrodeposited metals and use nontoxic chemicals, most metal fabricators possibly could apply these coatings and finishes in-house. The resulting cost savings could amount to thousands of dollars a year and at the same time give the fabricator complete control over the scheduling and manufacturing of the small parts.

The chemicals, metals, residues, and solutions used in phosphating processes are relatively nontoxic and may be neutralized easily for disposal into sewage systems or carried to disposal stations. Because they involve coatings and not electrodeposited processes (some of which are highly toxic and can cause environmental problems), the phosphating processes may not require a plating license.

13.6.1 Pickling formulas

Pickling solutions are used to chemically remove surface scale and oxides from metals and alloys. Typical formulas include

- One part sulfuric acid to 5 or 10 parts water by volume. Use for cleaning steel and other ferrous metals.
- Sulfuric acid and nitric acid; 1 part of each acid with 5 to 10 parts water by volume. Use for bright-cleaning brass alloys.
- Sulfuric acid and anhydrous ferric sulfate; 1 part acid to 5 or 10 parts water by volume, plus a small amount of ferric sulfate (1/10 part or less).

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- Chromium phosphate and triethanolamine. Use for preparing aluminum for painting.
- Phosphoric acid (75 percent); 1 part acid to 25 to 35 parts water by volume. Use for cleaning and phosphating steels in preparation for painting.

Note: Pickling baths must be maintained at a temperature of 145 to 185°F. Keep the pickling times short because hydrogen embrittlement can occur if the metal remains in the pickling bath for an excessive amount of time. Pickling-bath times vary from 3 to 15 minutes, with the shorter times preferred. As a precaution to avoid hydrogen embrittlement, the pickled parts may be oven heated at 300°F for 30 minutes.

13.6.2 Phosphate coatings (ferrous metals and alloys)

The four major types of phosphate coatings for ferrous metals and alloys include

1. Zinc phosphate
2. Iron phosphate
3. Manganese phosphate
4. Lead phosphate (a relatively new process)

Formulas for phosphating solutions and directions for their proper use are given in the following expositions and procedures.

Zinc phosphating. Zinc phosphate coatings are used on many military and commercial articles, including small arms, knives, heavy weapons and field artillery, tools, general mechanism parts, and a host of other fabricated metal applications. Zinc phosphating is also called *granodizing*.

To prepare 16 fluid oz (480 ml) of zinc phosphate concentrate, obtain the following ingredients:

- 33 g powdered zinc
- 436 ml phosphoric acid (75% to 85% solution)
- 110 ml distilled water

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- 10 to 12 g sodium nitrite (accelerator). (The amount of sodium nitrite may need to be adjusted to suit the application; potassium nitrite may be used in lieu of sodium nitrite.)

For a smaller base quantity of concentrate, use the following measures:

- 16.5 g powdered zinc
- 218 ml phosphoric acid (75% to 85% solution)
- 55 ml distilled water
- 5 to 6 g sodium nitrite (accelerator). (The amount of sodium nitrite may need to be adjusted to suit the application; potassium nitrite may be used in lieu of sodium nitrite.)

Procedure. Dissolve the powdered zinc in the phosphoric acid, and then add the distilled water and sodium nitrite. Mix thoroughly and filter through a stainless steel filter screen or paper filter. (Heat and outgassing occur during the acid/zinc mixing and dissolution.)

The finished zinc phosphate concentrate then may be mixed in the following phosphating solutions:

Solution I (normal): 16 fluid oz concentrate to 6.75 gal of water or 1 fluid oz of concentrate to 54 oz of water

Solution II (heavy): 16 fluid oz concentrate to 5 gal of water or 1 fluid oz of concentrate to 40 oz of water

Processing temperature is 170 to 180°F (recommended temperature is 175°F). Distilled water will yield the best results, but "soft" tap water is sufficient.

Processing time is 3 to 10 minutes. Longer processing times (10 minutes or more) deposit darker-colored and denser coatings and may be necessary for hardened steel parts such as firearm receivers and bolts. The phosphating process is usually self-terminating; chemical action will stop when the part is sufficiently coated.

Immediately rinse the phosphated parts in cold running water for 30 seconds. Do not allow the phosphating solution to dry on the phosphated part; otherwise, difficult-to-remove white deposits of zinc salts will form on the parts.

The parts then may be dipped into a mild solution of chromic acid and water (1 oz chromic acid to 1 gal of water). Then rinse the parts again in cold running water.

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Thoroughly dry the parts with compressed or blown hot air. Bake critical parts as outlined herein.

Coat the parts with a light oil, an oil-kerosene mix, or WD40 lubricant. Then remove or drain excess oil from the parts. The parts now may be assembled or stored for future use.

Note: As a safety precaution, hardened and highly stressed parts that have been phosphate treated for 10 minutes or longer should be baked at 300°F for 30 minutes to prevent hydrogen embrittlement.

Iron phosphating (reference only). Iron phosphating, also known as *coslettizing,* uses powdered iron and phosphoric acid in the solution. Accelerator chemicals such as sodium nitrite, potassium nitrate, and potassium nitrite are not normally required for iron phosphating processes.

Manganese phosphating (reference only). Manganese phosphating, also called *parkerizing*, uses powdered iron, manganese phosphate, and phosphoric acid in the solution.

Bonderizing. Bonderizing is performed on ferrous metals and alloys in a solution consisting of phosphoric acid, a catalyst, and water. This process is used to impart a rough, tough, frosted surface providing excellent paint adhesion. The phosphated coating is rust resistant.

Note: Phosphate coatings are on the general order of 0.0002 in (0.2 mil) thick. All phosphating solutions are used or processed at temperatures of 145 to 200°F. Immediate washing in cold water is recommended after the phosphate coating is applied to prevent white streaks or blemishes from appearing on the surface of the metal or alloy.

Phosphate coatings are most applicable for low-, medium-, and high-carbon steels in both the annealed and hardened conditions. Ferrous metal parts that have been highly hardened and some of the higher-alloy steels are more difficult to phosphate coat. On these steels, the phosphate coating will be light gray in color unless the part is immersion-coated for longer periods (10 minutes or longer). Stainless steels and other high-nickel-chromium steels cannot be phosphated.

The more iron a ferrous material contains, the thicker and darker will be the phosphate coating. Heavy zinc phosphate coatings are the easiest to apply, with some of the processes requiring only 3 to 5 minutes to complete. Ferrous materials that are case hardened normally cannot be phosphatized. If high-alloy ferrous parts need a

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heavier or darker coating, they may be processed in phosphating solutions up to double the time normally required, i.e., up to 10 to 15 minutes for the solutions used in the zinc phosphating process detailed in this disclosure.

13.7 Etching Metals

The solutions used to etch various metals are often called *mordants,* and some of the solutions used in the etching processes are as follows.

13.7.1 Etching irons, steels, and zinc plate

Nitric acid solution. A popular solution for etching irons, steels, and zinc plates consists of a solution of 2 oz 50% nitric acid mixed into 15 oz water. This is a 1:16 solution. Always pour the acid into the water; never pour water into the acid. Pouring water into acid may cause a mixing reaction that could result in acid splashing from the mixing container. The solution is relatively slow acting unless used with a splash-type etching machine. For hand etching, a stronger solution can be used, but the etching cut becomes rough at the edges of the etching action. Solutions as strong as 1:8 can be used: 1 part concentrated nitric acid to 7 parts water by volume.

13.7.2 Etching copper and copper alloys

Ferric chloride is often used to etch copper and its alloys. A 40°Bé solution of ferric chloride used at 75 to 80°F etches copper cleanly and not too rapidly so as to produce a rough etched edge. A 40°Bé solution is made by mixing 20 oz ferric chloride (anhydrous) with water to make a final volume of 1 liter (1000 ml). The specific gravity of this solution can be from 1.37 to 1.38. The designation 40°Bé (Baumé) is pronounced "40 degrees 'bow-may'" and is defined with respect to specific gravity by the following equation:

$$\text{Specific gravity} = \frac{145}{145 - {}^\circ\text{Bé}}$$

With this equation, you may determine the degrees Baumé if you know what specific gravity you want or have, or you may determine the specific gravity required of the solution if you know the degrees Baumé you wish to produce.

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Note: The reaction of ferric chloride produces a great amount of heat when it is dissolved in water. The water temperature should be between 50 and 75°F prior to mixing the ferric chloride solution.

Solutions of ferric chloride as low as 300°Bé are used for fast etching of copper and its alloys, while the 40 to 42°Bé solutions are used for etching intaglio printing plates or photogravure work. These solutions also have been used to etch stainless steels. The ferric chloride bath should be contained in a glass, plastic, or wooden tank because the solution is highly corrosive. Do not dispose of these solutions directly into standard drainage systems. The solutions should be diluted in water and neutralized with a base chemical such as sodium bicarbonate. Do not allow the solutions to come into contact with the skin; rubber gloves should be worn at all times during use of these solutions.

Printed circuit boards for electronic applications have been produced using ferric chloride solutions for many years. Using the lower °Bé solutions produces a fast and accurate etching action or cut, and the ferric chloride is economical and long lasting. Perchlorate chemicals are also used for etching printed circuit boards.

Frank Short's etching solution. The Frank Short etching solution has been used by printing plate makers and other metalworkers for years and is a slow-acting but very accurate etchant (mordant). The solution may be made as follows:

- 88 parts by volume distilled water
- 2 parts by volume potassium chloride
- 10 parts by volume hydrochloric acid (concentrated)

This is a two-part mixture that must be made by mixing two solutions and then pouring the two solutions together.

Solution 1. Mix 1 oz potassium chloride into 10 oz water at 190 to 200°F

Solution 2. Mix 5 oz hydrochloric acid into 34 oz distilled water

Then pour solution 1 into solution 2 in a well-ventilated area.

Caution: Chlorine gas is evolved when the two solutions are mixed. Allow the solution to sit for 30 minutes to 1 hour before using. Store in a glass bottle with a rubber or glass stopper.

The part to be etched is lowered into a shallow glass pan or tank so that the solution covers the part by approximately ½ in. The

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etching action may be observed directly because the etching solution is clear and transparent.

Copper and its alloys, irons and steels, and chromium-plated parts may be etched with this solution. Use adequate ventilation because chlorine gas in small amounts is evolved during the etching action. This solution is often used to check the etching mask for holes prior to fast etching in ferric chloride solutions. A copper part will begin to show a frosting effect a few seconds after immersion in the solution. Holes in the etching mask then may be seen and repaired prior to the final etching.

As a final note, titanium heaters are used in etching baths for ferric chloride solutions.

13.7.3 Etching aluminum and aluminum alloys

Most aluminum alloys can be etched using sodium hydroxide solutions of varying strengths. Sodium hydroxide is commonly called *caustic soda* or *lye* and is a low-cost chemical. Sodium hydroxide is very corrosive or caustic and is poisonous. When aluminums are etched using sodium hydroxide solutions, one of the reaction products is hydrogen gas, which is highly explosive when mixed with normal air. Proper venting must be employed when using this process for etching aluminum alloys.

The etching action is relatively rapid, especially if the sodium hydroxide solution is above 1:16 (1 part sodium hydroxide to 15 parts water). Strong solutions produce a violent foaming reaction and substantial amounts of hydrogen gas.

Conversion formulas for chemical solutions. Figure 13.18 shows the conversion formulas for solutions having concentrations expressed in various ways.

13.8 Anodizing

Anodizing is a process of oxidation produced in an electrolytic bath. Aluminum and its alloys are most commonly anodized, although the anodizing process may be performed on magnesium, zinc, and titanium. This section will cover the anodize coatings and processes for aluminum and its alloys only. The anodic coating, being aluminum oxide, is extremely hard and abrasive, especially aluminum hardcoat anodized surfaces. The classifications for aluminum and aluminum alloy anodic coatings are as follows.

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CONVERSION FORMULAE FOR SOLUTIONS HAVING CONCENTRATIONS EXPRESSED IN VARIOUS WAYS

A = Weight per cent of solute
B = Molecular weight of solvent
E = Molecular weight of solute
F = Grams of solute per liter of solution
G = Molality
M = Molarity
N = Mole fraction
R = Density of solution grams per cc

Concentration of solute—SOUGHT	Concentration of solute—GIVEN				
	A	B	G	M	F
A	—	$\frac{100N \times E}{N \times E + (1 - N)B}$	$\frac{100G \times E}{1000 + G \times E}$	$\frac{M \times E}{10R}$	$\frac{F}{10R}$
B	$\frac{\frac{A}{E}}{\frac{A}{E} + \frac{100 - A}{B}}$	—	$\frac{B \times G}{B \times G + 1000}$	$\frac{B \times M}{M(B - E) + 1000R}$	$\frac{B \times F}{F(B - E) + 1000R \times E}$
G	$\frac{1000A}{E(100 - A)}$	$\frac{100N}{B - N \times B}$	—	$\frac{1000M}{1000R - (M \times E)}$	$\frac{1000F}{E(1000R - F)}$
M	$\frac{10R \times A}{E}$	$\frac{10R \times N}{N \times E + (1 - N)B}$	$\frac{1000R \times G}{1000 + E \times G}$	—	$\frac{F}{E}$
F	10AR	$\frac{10R \times N \times E}{N \times E + (1 - N)B}$	$\frac{1000R \times G \times E}{1000 + G \times E}$	$M \times E$	—

Figure 13.18 Solution conversion equations. *(Source: Handbook of Chemistry and Physics, 50th ed., Chemical Rubber Publishing Company, Cleveland, Ohio.)*

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Classifications

Type I. Chromic acid anodizing, conventional coatings produced from chromic acid baths. Shall not be applied to alloys containing over 5% copper or over 7% silicon or when alloying elements exceed 7.5%.

Type IB. Chromic acid anodizing, low-voltage process, 20 V. Heat-treatable alloys, such as T4, T6, etc., should be tempered prior to anodizing.

Type II. Sulfuric acid anodizing, conventional coatings produced from sulfuric acid baths. Heat-treatable alloys, such as T4, T6, etc., should be tempered prior to anodizing.

Type III. Hard anodic coatings (hardcoat). Shall not be applied to alloys containing over 5% copper or over 8% silicon unless agreed on by the supplier. Heat-treatable alloys, such as T4, T6, etc., should be tempered.

Classes

Class 1. Nondyed, natural, including dichromate sealing

Class 2. Dyed

Standard specifications for anodized aluminum and aluminum alloys

ASTM B244, *Thickness of Anodic Coatings, Measurement of*

ANSI/ASTM B137, *Weight of Coatings on Anodized Aluminum, Measurement of*

ASTM B117, *Method of Salt Spray (Fog) Testing*

Sealing anodized aluminum and aluminum alloys. All types of anodizing must be sealed using any of the following methods after the electrolytic anodized coating is applied:

- Immersion in an aqueous solution of 5% sodium dichromate (15 min at 90 to 100°C)
- Immersion in deionized water (15 min at 100°C)
- Immersion in an aqueous solution of nickel or cobalt acetate (100°C for 15 min)
- Teflon impregnation processes (for sealing and lubricity)

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Anodic coating design data

Radii of curvature on anodized parts

Nominal coating thickness, in	Radius of curvature (outside/inside), in
0.001	approx. 0.032
0.002	approx. 0.062
0.003	approx. 0.093
0.004	approx. 0.125

Thickness ranges of anodic coatings on aluminum and aluminum alloys

Coating type	Thickness range, in
I and IB	0.00002 to 0.0003
II	0.00007 to 0.0010
III	0.0005 to 0.0045

Minimum thickness (typical) of anodic coatings on aluminum and alloys. See Fig. 13.19 for minimum typical anodic coating thicknesses on various aluminum alloys per type.

Maximum thicknesses of anodic coatings on various aluminum alloys. Figure 13.20 shows the maximum attainable thicknesses of anodic coatings on selected aluminum alloys.

Design notes for anodized parts

1. A 2-mil hardcoat anodic coating (0.002 in) will penetrate the part 0.001 in and protrude from the part 0.001 in. A 1.000-in-diameter part that is anodized 2 mils (0.002 in) will have a finished diameter of 1.002 in. Half the coating is inside the part, and half is on the outside.
2. Avoid blind holes in parts.
3. Avoid hollow weldments (drill 0.250-in-diameter weep holes in the part).
4. Avoid steel inserts.
5. Avoid sharp corners (see radii chart above).
6. Avoid heavy to thin cross sections on the part.
7. Allow for the anodic coating in your design tolerances on the part.

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Plating Practices and Finishes for Metal

Minimum Typical Anodic Coating Thicknesses for Various Aluminum Alloys

Alloy Designation	Thickness of Coating, inches	
	Type I and IB	Type II
1100	0.000029	0.000093
2024-T4	.....	0.000125
2024-T6	0.000044	.....
3003	0.000035	0.000103
5052	0.000033	0.000098
5056	0.000021	.....
6061-T6	0.000034	0.000099
7075-T6	0.000040	.....
Alclad 2014-T6	0.000045	.....
Alclad 7075-T6	0.000041	.....
295-T6	.....	0.000107
356-T6	.....	0.000102
514	.....	0.000086

Note: Anodic coating types I, IB and II are normally applied as thin coats, while type III (Hardcoat) is normally applied as the thicker coatings. See table of anodic thicknesses in Figure 13-20.

Figure 13.19 Anodic coating thickness.

Anodic coating specifications

Name	Hardcoat anodize	Chromic anodize	Sulfuric anodize
Army/Navy	Mil-A-8625, Ty-3	Mil-A-8625, Ty-1	Mil-A-8625, Ty-2
G.E.	AMS-2468D	AMS-2470H	AMS-2471D
Boeing	Code-302	Code-300	Code-301
IBM	41-207	41-204	41-203
Grumman	G-9031	9030B	G-9032

Hardcoat anodize processes

- Martin
- Alumilite
- Alpha
- Mae

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Maximum Anodic Coating Thicknesses on Various Aluminum Alloys

Alloy Designation	Anodic Coating Thickness - inches	Color
380	0.0006	Gray
360	0.001	Gray
319	0.0014	Gray
1100	0.0017	Bronze
2011	0.0021	Light gray
2014	0.0025	Gray
2019	0.0028	Bronze
6262	0.0031	Black
6061	0.0035	Black
2024	0.0040	Bronze
2017	0.0045	Bronze
6063	0.0050	Black
5052	0.0053	Black
2618	0.0055	Gray
2219	0.0058	Gray
218	0.0062	Gray
7079	0.0065	Dark gray
355	0.0075	Gray
7075	0.0082	Bronze
Almag 35	0.0100	Gray
356	0.0120	Light gray

Note: All above coatings may be dyed black. Coatings over 0.003 inches thick tend to chip and become milky in color and should be used only in the salvage of parts.
Source: Anodic, Inc., Stevenson, CT 06491.

Figure 13.20 Maximum anodic coating thickness.

- Sanford
- Boeing
- Scionic
- Hardas
- Imperv-X

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Hardcoat/Teflon processes

- Amphodize
- Hardtef
- Analon
- Tufram
- Polylube
- Lukon
- Nituf
- Kalon
- PTFE
- Smoothcoat
- Sanfordize
- Hardlube

Hardcoat anodize physical data

Hardness	65 to 70 Rockwell C Scale (Harder than Hard Chrome)
Color	Dark gray to black
Dielectric strength	800 V/mil
Machining	Grinding, lapping, polishing, and honing
Sealing	Dichromate, nickel, or cobalt acetate, hot water or Teflon impregnation
Resistivity	10^8 to 10^{12} Ω·cm

Note: Parts that have been anodized cannot be reanodized, nor can the anodic coating be made thicker.

13.9 Paint Finishing

Paints are the most used of all finishes for metal products. The types and different varieties and colors available are limitless. Paint technology improves and changes constantly. Attesting to the quality and long-lasting ability of modern paints for metals are automotive vehicles and aircraft. Not only must modern industrial paints withstand the weather and corrosive elements, but many also are protected chemically from the harmful effects of ultraviolet radiation from the sun.

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Common industrial paints include

- Enamels (baked and air drying)
- Lacquers
- Epoxies (one- and two-part systems)
- Varnishes (glyptols, polyurethanes, and special chemical resistant)
- Latex/water-based

Pigments such as zinc and titanium oxide, carbon black, zinc chromate, Prussian blue, cobalt blue, and many others can be added to the paint for coloring and to improve durability.

Products that are built to customer or military specifications frequently have the type of finish listed in the specifications, together with the method of base-metal preparation, such as phosphatizing, zinc chromate primer, zinc primer, etc. The color and the required minimum dry-film paint thickness also frequently are set out in the equipment specifications.

Some of the high-quality equipment manufacturers in the United States apply multiple coatings to their products, producing a finish that is not only attractive but also long-lasting and durable. Large equipment, primarily made of sheet steel, as emphasized in the switch-gear manufacturing industry, often will be multiply coated. Some of the manufacturers use a phosphatizing process on the bare metal, followed by a zinc-based primer, which is then epoxy coated and finally given a high-quality polyurethane paint finish. Equipment of this caliber can be expected to withstand outdoor weathering for many years without finish problems.

When the base metal of equipment is improperly prepared and then given a few coats of low-quality finish, corrosion usually begins soon after the equipment is exposed to the elements. Finish problems on large, fabricated metal equipment and structures are often a serious defect, and it becomes difficult to prevent further corrosion, even though repainting is undertaken. If the base-metal preparation and primers are not selected or applied correctly, corrosion problems always will be prevalent.

Specific design questions and requirements for the paint finish must be directed to the proper paint manufacturer if high-quality results are expected. High-quality paints and correct base-metal preparation techniques are expensive and require the proper equipment and facilities. There are many government regulations in force

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today that stipulate the procedures to be followed for environmental protection relative to the use of paint finishes. These regulations are formulated and enforced by the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA). Chapter 15, "Safety Practices in Industry," lists the OSHA standards that help to protect workers from industrial hazards caused by many substances and improper manufacturing practices, including paint ingredients and by-products.

13.9.1 Estimating paint-film thickness and coverage

Estimating the quantity of materials for a painting project is not as simple as one might expect. The surface-area coverage of any particular paint is usually listed on the paint container. But this coverage is for average wet-film area and does not take into consideration the dry-film thickness required on the product.

To determine the coverage for a 1-mil (0.001-in) dry-film thickness for a paint containing less than 100 percent solids, multiply the percentage of nonvolatile solids by 1604 and divide by 100. The percentage of nonvolatile solids is found on the paint container label or from the paint manufacturer's literature. The wet-film thickness required for a specific dry-film thickness is found by dividing the desired dry-film thickness by the percentage of solids by volume of the coating to be used. (Wet-film thickness is measured during application by a wet-film thickness gauge.)

A fast and accurate estimate of wet-film thickness required to obtain a specified dry-film thickness and theoretical coverage in square feet of area per gallon can be made using the nomograph shown in Fig. 13.21. To use the nomograph, connect the dry-film thickness on scale D with the percentage of solids on scale S, and read the wet-film thickness required on scale T together with the square feet of coverage per gallon.

13.10 Powder Coating

Powder coating is one of the newer finishing technologies; however, its use has increased in recent years to the point where it now accounts for approximately 10 percent of all industrial finishing applications. Powder coating generally involves spraying electrostatically charged powder consisting of pigment and resin onto the surface of a grounded metal part. The powder sticks to the surface

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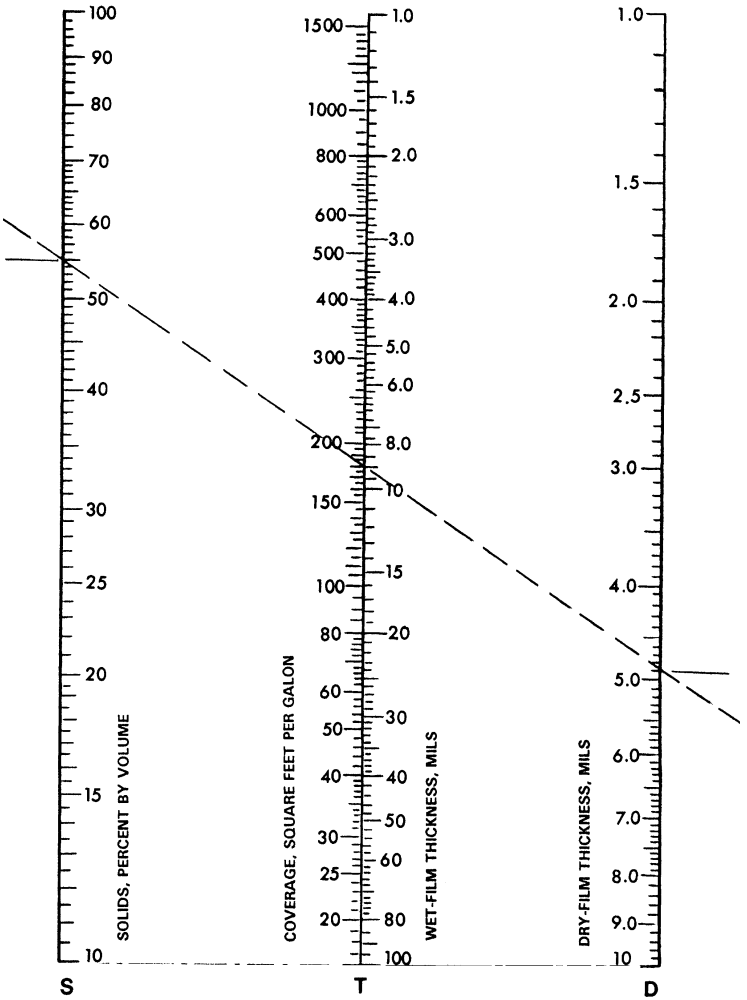

Figure 13.21 Wet-film to dry-film paint-finish nomograph.

of the part owing to the electrostatic attraction. Two types of powders are used: thermoplastics and cross-linked thermosets. Following the spraying operation, the coated part is passed through a furnace to melt (thermoplastic) or cure (thermoset) the powder. The parts being coated often are hung from a closed-loop overhead conveyor chain that moves the parts from one finishing step to the next.

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There are two very significant advantages to powder coatings compared with more conventional paint-spray techniques. Because the powders are not suspended in solvents as is the case with most paints, the powder-coating process produces few, if any, volatile organic compounds. It is therefore a relatively environmentally friendly coating process. Another advantage of the process is its high material utilization. Any powder that does not adhere to the surface of the part is filtered and reused. Material utilization therefore approaches 95 percent. This is much higher than is the case with spray painting, where the overspray is generally lost.

Powder coating of steels. As is the case with finishing any metal, the first step is to clean any greases, oils, or other contaminants from the surface. Parts intended strictly for interior use are then given an iron phosphate conversion coating as described in Sec. 13.6.2. The conversion coating and a subsequent acid rinse serve to enhance adhesion of the powder coating. Parts intended for outside use also must be galvanized to improve corrosion resistance. This is done by first applying a grain refiner that is followed by a zinc phosphate dip (see Sec. 13.6.2) and an acid rinse. The grain refiner produces a smoother surface. The part is then ready to accept its powder coating.

Powder coating of aluminum alloys. The parts to be powder coated are first cleaned thoroughly with a detergent solution. The surface is then etched as described elsewhere in this chapter to remove the oxide skin. A chromate or phosphate conversion coating is then applied to enhance adhesion of the powder coating. The aluminum part is then ready for the application of powder coating.

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Chapter

14

Fastening and Joining Techniques and Hardware

14.1 Bolts, Screws, Nuts, and Washers

Bolts and screws are the most commonly used types of fastening devices. The thread on a bolt or screw may be compared with an inclined plane wrapped around a cylinder, thus assuming the form of one of the basic machines. Many different thread-form standards are used throughout the world, but this chapter addresses only the forms in common use, such as the 60° V thread form for the U.S. Customary (inch) system and the metric [International Standards Organization (ISO)] standard. The other basic thread forms and their geometry are shown in Chap. 7, "Machining, Machine Tools, and Practices."

14.1.1 Dimensions of bolts, screws, nuts, and washers

Basic dimensions for the most commonly used American standard bolts are shown in Fig. 14.1. Basic dimensions for the most commonly used American standard machine screws are shown in Fig. 14.2. Basic dimensions for American standard miniature screws are shown in Fig. 14.3.

The dimensions shown in these figures are the most important ones needed for machining clearances and tool/design engineering purposes. The complete dimensional specifications and applicable

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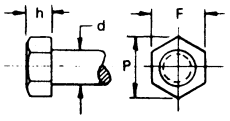
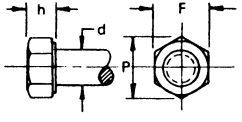
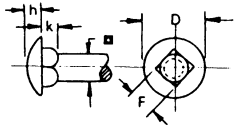
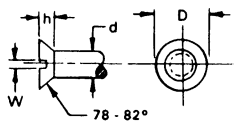
Nominal size	Hex Bolts				Hex Cap Screw (Finished Hex Bolts)				Round Head Square Neck Bolts				Countersunk Bolts			
																
Basic Dia.	d	F	P	h	d	F	P	h	D	F	h	k	d	D	h	W ♦
0.2500 - 1/4	0.260	0.438	0.505	0.188	0.2500	0.438	0.505	0.163	0.594	0.260	0.145	0.156	0.260	0.493	0.150	0.064
0.3125 - 5/16	0.324	0.500	0.577	0.235	0.3125	0.500	0.577	0.211	0.719	0.324	0.176	0.187	0.324	0.618	0.189	0.072
0.3750 - 3/8	0.388	0.562	0.650	0.268	0.3750	0.562	0.650	0.243	0.844	0.388	0.208	0.219	0.388	0.740	0.225	0.081
0.4375 - 7/16	0.452	0.625	0.722	0.316	0.4375	0.625	0.722	0.291	0.969	0.452	0.239	0.250	0.452	0.803	0.226	0.081
0.5000 - 1/2	0.515	0.750	0.866	0.364	0.5000	0.750	0.866	0.323	1.094	0.515	0.270	0.281	0.515	0.935	0.269	0.091
0.5625 - 9/16	-----	-----	-----	-----	0.5625	0.812	0.938	0.371	-----	-----	-----	-----	-----	-----	-----	-----
0.6250 - 5/8	0.642	0.938	1.083	0.444	0.6250	0.938	1.083	0.403	1.344	0.642	0.344	0.344	0.642	1.169	0.336	0.116
0.7500 - 3/4	0.768	1.125	1.299	0.524	0.7500	1.125	1.299	0.483	1.594	0.768	0.406	0.406	0.768	1.402	0.403	0.131
0.8750 - 7/8	0.895	1.312	1.516	0.604	0.8750	1.312	1.516	0.563	1.844	0.895	0.469	0.469	0.895	1.637	0.470	0.147
1.0000 - 1	1.022	1.500	1.732	0.700	1.0000	1.500	1.732	0.627	2.094	1.022	0.531	0.531	1.022	1.869	0.537	0.166
1.1250 - 1-1/8	1.149	1.688	1.949	0.780	1.1250	1.688	1.949	0.718	-----	-----	-----	-----	1.149	2.104	0.604	0.178
1.2500 - 1-1/4	1.277	1.875	2.165	0.876	1.2500	1.875	2.165	0.813	-----	-----	-----	-----	1.277	2.337	0.671	0.193
1.3750 - 1-3/8	1.404	2.062	2.382	0.940	1.3750	2.062	2.382	0.878	-----	-----	-----	-----	1.404	2.571	0.738	0.208
1.5000 - 1-1/2	1.531	2.250	2.598	1.036	1.5000	2.250	2.598	0.974	-----	-----	-----	-----	1.531	2.804	0.805	0.240
1.7500 - 1-3/4	1.785	2.625	3.031	1.196	1.7500	2.625	3.031	1.134	-----	-----	-----	-----	-----	-----	-----	-----
2.0000 - 2	2.039	3.000	3.464	1.388	2.0000	3.000	3.464	1.263	-----	-----	-----	-----	-----	-----	-----	-----

Note: ♦ Minimum dimensions of slot widths. All other tabulated values are maximum dimensions. ◘ diameters same as hex bolts (d) of same basic size.

Figure 14.1 Dimensions for American standard bolts.

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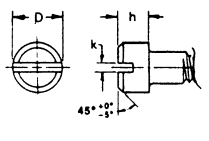
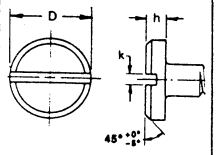
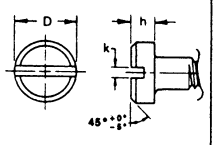
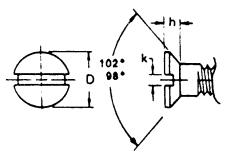
Nominal Size		Fillister Head			Binding Head			Pan Head			Countersunk			Undercut C'sunk		
Basic Dia.		D	h	k♦	D	h	k♦	D	h	k♦	D	h	k♦	D	h	k♦
0 -	0.0600	0.096	0.055	0.016	0.126	0.032	0.016	0.116	0.039	0.016	0.119	0.035	0.016	0.119	0.025	0.016
1 -	0.0730	0.118	0.066	0.019	0.153	0.041	0.019	0.142	0.046	0.019	0.146	0.043	0.019	0.146	0.031	0.019
2 -	0.0860	0.140	0.083	0.023	0.181	0.050	0.023	0.167	0.053	0.023	0.172	0.051	0.023	0.172	0.036	0.023
3 -	0.0990	0.161	0.095	0.027	0.208	0.059	0.027	0.193	0.060	0.027	0.199	0.059	0.027	0.199	0.042	0.027
4 -	0.1120	0.183	0.107	0.031	0.235	0.068	0.031	0.219	0.068	0.031	0.225	0.067	0.031	0.225	0.047	0.031
5 -	0.1250	0.205	0.120	0.035	0.263	0.078	0.035	0.245	0.075	0.035	0.252	0.075	0.035	0.252	0.053	0.035
6 -	0.1380	0.226	0.132	0.039	0.290	0.087	0.039	0.270	0.082	0.039	0.279	0.083	0.039	0.279	0.059	0.039
8 -	0.1640	0.270	0.156	0.045	0.344	0.105	0.045	0.322	0.096	0.045	0.332	0.100	0.045	0.332	0.070	0.045
10 -	0.1900	0.313	0.180	0.050	0.399	0.123	0.050	0.373	0.110	0.050	0.385	0.116	0.050	0.385	0.081	0.050
12 -	0.2160	0.357	0.205	0.056	0.454	0.141	0.056	0.425	0.125	0.056	0.438	0.132	0.056	0.438	0.092	0.056
1/4-	0.2500	0.414	0.237	0.064	0.525	0.165	0.064	0.492	0.144	0.064	0.507	0.153	0.064	0.507	0.107	0.064
5/16-	0.3125	0.518	0.295	0.072	0.656	0.209	0.072	0.615	0.178	0.072	0.635	0.191	0.072	0.635	0.134	0.072
3/8-	0.3750	0.622	0.335	0.081	0.788	0.253	0.081	0.740	0.212	0.081	0.762	0.230	0.081	0.762	0.161	0.081
7/16-	0.4375	0.625	0.368	0.081	-----	-----	-----	0.863	0.247	0.081	0.812	0.223	0.081	0.812	0.156	0.081
1/2-	0.5000	0.750	0.412	0.091	-----	-----	-----	0.987	0.281	0.091	0.875	0.223	0.091	0.875	0.156	0.091

Note: ♦ Minimum dimensions of slot widths. All other tabulated values are maximum dimensions.

Figure 14.2 Dimensions for standard machine screws.

Size	Thds/in	Basic dia.	Fillister			Binding			Pan			100° Flat Head		
														
			D	h	k♦	D	h	k♦	D	h	k♦	D	h	k♦
30 UNM	318	0.0118	0.021	0.012	0.003	----	----	----	0.025	0.010	0.003	0.023	0.007	0.003
40 UNM	254	0.0157	0.025	0.016	0.003	0.041	0.010	0.004	0.033	0.012	0.004	0.029	0.008	0.003
50 UNM	203	0.0197	0.033	0.020	0.004	0.051	0.012	0.005	0.041	0.016	0.005	0.037	0.011	0.004
60 UNM	169	0.0236	0.041	0.025	0.005	0.062	0.016	0.007	0.051	0.020	0.007	0.045	0.013	0.005
80 UNM	127	0.0315	0.051	0.032	0.007	0.082	0.020	0.008	0.062	0.025	0.008	0.056	0.016	0.007
100 UNM	102	0.0394	0.062	0.040	0.008	0.103	0.025	0.012	0.082	0.032	0.012	0.072	0.019	0.008
120 UNM	102	0.0472	0.082	0.050	0.012	0.124	0.032	0.015	0.103	0.040	0.015	0.092	0.025	0.012

Note: ♦ Minimum dimensions of slot widths. All other tabulated values are maximum dimensions.

Figure 14.3 Dimensions for standard miniature screws.

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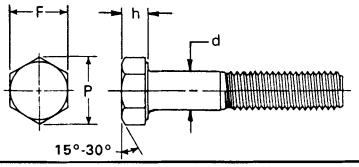
Fastening and Joining Techniques and Hardware

tolerances for all standard hardware or fasteners should be obtained from the fastener handbooks distributed by the Industrial Fasteners Institute (IFI) (see Sec. 16.1).

The design specifications for strength of all types of threaded fasteners are shown in a subsection to follow. In addition, the normal tightening torques required for bolts and screws will be shown in another subsection to follow. Calculation procedures for bolts and screws likewise will be presented in a later subsection.

Figure 14.4 shows the basic dimensions for metric hex-cap screws. Figure 14.5 shows the dimensions of American standard hex nuts and jamb nuts. Figure 14.6 shows the dimensions of metric standard nuts, type 1. Figure 14.7 shows the dimensions of American standard flat washers. Figure 14.8 shows dimensions of metric standard flat washers.

Figure 14.9 shows dimensions of American standard shoulder bolts and socket-head cap screws, which are used widely in tooling applications, as well as in other mechanical design applications.



Diameter & thread pitch	d	F	P	h
M5 - 0.8	5.00	8.00	9.24	3.65
M6 - 1	6.00	10.00	11.55	4.15
M8 - 1.25	8.00	13.00	15.01	5.50
M10 - 1.50	10.00	16.00	18.48	6.63
M12 - 1.75	12.00	18.00	20.78	7.76
M14 - 2	14.00	21.00	24.25	9.09
M16 - 2	16.00	24.00	27.71	10.32
M20 - 2.5	20.00	30.00	34.64	12.88
M24 - 3	24.00	36.00	41.57	15.44
M30 - 3.5	30.00	46.00	53.12	19.48
M36 - 4	36.00	55.00	63.51	23.38

Note: Tabulated dimensions are in millimeters and are maximum values.

Figure 14.4 Dimensions for metric hex-cap screws.

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Size	Flats	Points	Thickness
#0	5/32	0.180	0.050
#1	5/32	0.180	0.050
#2	3/16	0.217	0.066
#3	3/16	0.217	0.066
#4	1/4	0.289	0.098
#5	5/16	0.361	0.114
#6	5/16	0.361	0.114
#8	11/32	0.397	0.130
#10	3/8	0.433	0.130
1/4	7/16	0.505	0.226 0.163, jamb nut
5/16	1/2	0.577	0.273 0.195, jamb nut
3/8	9/16	0.650	0.337 0.227, jamb nut
7/16	11/16	0.794	0.385 0.260, jamb nut
1/2	3/4	0.866	0.448 0.323, jamb nut
5/8	15/16	1.083	0.559 0.387, jamb nut
3/4	1-1/8	1.299	0.665 0.446, jamb nut
7/8	1-5/16	1.516	0.776 0.510, jamb nut
1	1-1/2	1.732	0.887 0.575, jamb nut

Figure 14.5 Dimensions for American standard hex and jamb nuts.

Standard shoulder screw mechanical data

Thread class	UNC-3A (ANSI/ASME B1.3) (No plating allowance is provided.)
Material	Alloys of chrome, nickel, molybdenum, or vanadium
Hardness	32 to 43 Rockwell C at the surface
Ultimate tensile strength	140,000 lb/in^2 based on minimum thread neck area
Shear strength	84,000 lb/in^2 in thread neck and shoulder areas

14.1.2 Set, self-tapping, thread-forming, and wood screws

Figures 14.10 and 14.11 show the American standard socket set screws with dimensions and applications data. The size of the hex wrench required for each set-screw size is also shown. Figure 14.12

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Size	Flats	Points	Thickness
M1.6x0.35	3.20	3.70	1.30
M2x0.4	4.00	4.62	1.60
M2.5x0.45	5.00	5.77	2.00
M3x0.5	5.50	6.35	2.40
M3.5x0.6	6.00	6.93	2.80
M4x0.7	7.00	8.08	3.20
M5x0.8	8.00	9.24	4.70
M6x1	10.00	11.55	5.20
M8x1.25	13.00	15.01	6.80
M10x1.5	16.00	18.48	8.40
M12x1.75	18.00	20.78	10.80
M14x2	21.00	24.25	12.80
M16x2	24.00	27.71	14.80
M20x2.5	30.00	34.64	18.00
M24x3	36.00	41.57	21.50
M30x3.5	46.00	53.12	25.60
M36x4	55.00	63.51	31.00

NOTE: Tabulated dimensions are in millimeters. 1mm = 0.03937 inches.

Figure 14.6 Dimensions for metric standard nuts, hexagonal.

Size	Outside Diameter	Thickness
#0	3/16	0.028
#1	7/32	0.028
#2	1/4	0.036
#3	5/16	0.036
#4	3/8	0.045
#5	13/32	0.045
#6	7/16	0.045
#8	1/2	0.045
#10	9/16	0.045
¼	47/64	0.071
5/16	7/8	0.071
3/8	1	0.071
7/16	1-1/8	0.071
½	1-1/4	0.112
5/8	1-3/4	0.112
¾	2	0.112
7/8	2-1/4	0.174
1	2-1/2	0.174

Figure 14.7 Dimensions for American standard flat washers.

shows a chart of the standard self-tapping and thread-forming screws. Types AB, A, B, BF, and C are thread-forming, whereas types D, F, G, T, BF, and BT are thread-cutting or self-tapping. Type U is a spiral screw type that is driven or press-fit into the appropriately sized hole. All thread forms shown are 60° V thread.

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Size	Series	Outside Diameter	Thickness
1.6	Narrow	4.00	0.70
	Regular	5.00	0.70
	Wide	6.00	0.90
2	Narrow	5.00	0.90
	Regular	6.00	0.90
	Wide	8.00	0.90
2.5	Narrow	6.00	0.90
	Regular	8.00	0.90
	Wide	10.00	1.20
3	Narrow	7.00	0.90
	Regular	10.00	1.20
	Wide	12.00	1.40
3.5	Narrow	9.00	1.20
	Regular	10.00	1.40
	Wide	15.00	1.75
4	Narrow	10.00	1.20
	Regular	12.00	1.40
	Wide	16.00	2.30
5	Narrow	11.00	1.40
	Regular	15.00	1.75
	Wide	20.00	2.30
6	Narrow	13.00	1.75
	Regular	18.80	1.75
	Wide	25.40	2.30
8	Narrow	18.80	2.30
	Regular	25.40	2.30
	Wide	32.00	2.80
10	Narrow	20.00	2.30
	Regular	28.00	2.80
	Wide	39.00	3.50
12	Narrow	25.40	2.80
	Regular	34.00	3.50
	Wide	44.00	3.50
14	Narrow	28.00	2.80
	Regular	39.00	3.50
	Wide	50.00	4.00
16	Narrow	32.00	3.50
	Regular	44.00	4.00
	Wide	56.00	4.60
20	Narrow	39.00	4.00
	Regular	50.00	4.60
	Wide	66.00	5.10
24	Narrow	44.00	4.60
	Regular	56.00	5.10
	Wide	72.00	5.60
30	Narrow	56.00	5.10
	Regular	72.00	5.60
	Wide	90.00	6.40
36	Narrow	66.00	5.60
	Regular	90.00	6.40
	Wide	110.00	8.50

Note: Tabulated dimensions are in millimeters.

Figure 14.8 Dimensions for metric standard flat washers.

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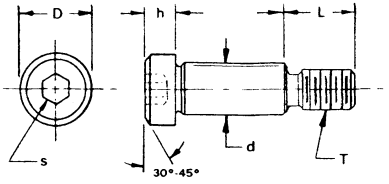

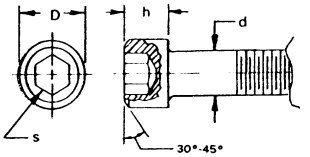

Nominal size		d	D	h	s	T	L	d	D	h	s
4	0.1120	----	----	----	----	----	----	0.1120	0.183	0.112	0.094
5	0.1250	----	----	----	----	----	----	0.1250	0.205	0.125	0.094
6	0.1380	----	----	----	----	----	----	0.1380	0.226	0.138	0.109
8	0.1640	----	----	----	----	----	----	0.1640	0.270	0.164	0.141
10	0.1900	----	----	----	----	----	----	0.1900	0.312	0.190	0.156
1/4	0.2500	0.2480	0.375	0.188	0.125	0.190-24	0.375	0.2500	0.375	0.250	0.188
5/16	0.3125	0.3105	0.438	0.219	0.156	0.250-20	0.438	0.3125	0.469	0.312	0.250
3/8	0.3750	0.3730	0.562	0.250	0.188	0.312-18	0.500	0.3750	0.562	0.375	0.312
7/16	0.4375	----	----	----	----	----	----	0.4375	0.656	0.438	0.375
1/2	0.5000	0.4980	0.750	0.312	0.250	0.375-16	0.625	0.5000	0.750	0.500	0.375
5/8	0.6250	0.6230	0.875	0.375	0.312	0.500-13	0.750	0.6250	0.938	0.625	0.500
3/4	0.7500	0.7480	1.000	0.500	0.375	0.625-11	0.875	0.7500	1.125	0.750	0.625
7/8	0.8750	----	----	----	----	----	----	0.8750	1.312	0.875	0.750
1	1.0000	0.9980	1.312	0.625	0.500	0.750-10	1.000	1.0000	1.500	1.000	0.750
1-1/8	1.1250	----	----	----	----	----	----	1.1250	1.688	1.125	0.875
1-1/4	1.2500	1.2480	1.750	0.750	0.625	0.875-9	1.125	1.2500	1.875	1.250	0.875
1-3/8	1.3750	----	----	----	----	----	----	1.3750	2.062	1.375	1.000
1-1/2	1.5000	1.4980	2.125	1.000	0.875	1.125-7	1.500	1.5000	2.250	1.500	1.000
1-3/4	1.7500	1.7480	2.375	1.125	1.000	1.250-7	1.750	1.7500	2.625	1.750	1.250
2	2.0000	1.9980	2.750	1.250	1.250	1.500-6	2.000	2.0000	3.000	2.000	1.500

Note: All tabulated dimensions are maximum values. See text for materials, hardness, etc.

Figure 14.9 American standard socket-head shoulder screws and socket-head cap screws.

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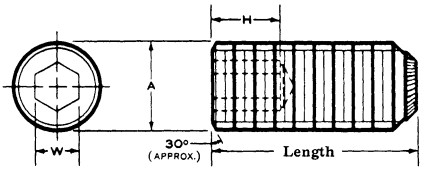

Dimensions

size	threads per inch UNC	threads per inch UNF	A max.	A min. UNC	A min. UNF	C max.	C min.	D max.	D min.	F max.	F min.	H min.	W nom.
#0	....	80	.0600	....	.0568	.033	.027	.040	.037	.017	.013	.022	.028
#1	64	72	.0730	.0692	.0695	.040	.033	.049	.045	.021	.017	.028	.035
#2	56	64	.0860	.0819	.0822	.047	.039	.057	.053	.024	.020	.028	.035
#3	48	56	.0990	.0945	.0949	.054	.045	.066	.062	.027	.023	.040	.050
#4	40	48	.1120	.1069	.1075	.061	.051	.075	.070	.030	.026	.040	.050
#5	40	44	.1250	.1199	.1202	.067	.057	.083	.078	.033	.027	.050	.0625
#6	32	40	.1380	.1320	.1329	.074	.064	.092	.087	.038	.032	.050	.0625
#8	32	36	.1640	.1580	.1585	.087	.076	.109	.103	.043	.037	.062	.0781
#10	24	32	.1900	.1828	.1840	.102	.088	.127	.120	.049	.041	.075	.0937
1/4	20	28	.2500	.2419	.2435	.132	.118	.156	.149	.0565	.0585	.100	.125
5/16	18	24	.3125	.3038	.3053	.172	.156	.203	.195	.082	.074	.125	.1562
3/8	16	24	.3750	.3656	.3678	.212	.194	.250	.241	.0987	.0887	.150	.1875
7/16	14	20	.4375	.4272	.4294	.252	.232	.296	.287	.114	.104	.175	.2187
1/2	13	20	.5000	.4891	.4919	.291	.270	.343	.334	.130	.120	.200	.250
9/16	12	18	.5625	.5511	.5538	.332	.309	.390	.379	.1456	.1356	.200	.250
5/8	11	18	.6250	.6129	.6163	.371	.347	.468	.456	.164	.148	.250	.3125
3/4	10	16	.7500	.7371	.7406	.450	.425	.562	.549	.1955	.1795	.300	.375
7/8	9	14	.8750	.8611	.8647	.530	.502	.656	.642	.2267	.2107	.400	.500
1	8	12	1.0000	.9850	.9886	.609	.579	.750	.734	.260	.240	.450	.5625
1 1/8	7	12	1.1250	1.1086	1.1136	.689	.655	.843	.826	.291	.271	.450	.5625
1 1/4	7	12	1.2500	1.2336	1.2386	.767	.733	.937	.920	.3225	.3025	.500	.625
1 3/8	6	12	1.3750	1.3568	1.3636	.848	.808	1.031	1.011	.3537	.3337	.500	.625
1 1/2	6	12	1.5000	1.4818	1.4886	.926	.886	1.125	1.105	.385	.365	.600	.750

Figure 14.10 Socket set-screw dimensions.

Holes for self-tapping and thread-forming screws. Extensive tables of recommended hole sizes for self-tapping and thread-forming screws are available from screw manufacturers. Because of the great variety of materials and thickness ranges possible for applying these types of screws, no tables are given here. In actual practice, you may measure the outside diameter of the screw thread and the root diameter and then take the mean difference to find an approximate hole diameter for the particular screw and material combination. A few trial combinations will give you the exact drill size to use for your application.

Figure 14.13 shows American standard wood screws and their dimensions. Wood screws are used by pattern makers and in wooden form blocks for vacuum-forming equipment applications (vacuum-

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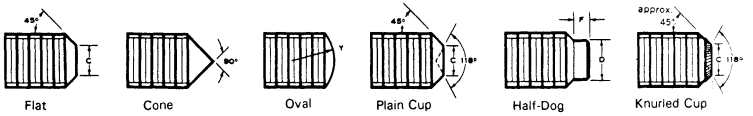
Point Types



Flat Cone Oval Plain Cup Half-Dog Knurled Cup

Application Data

Y	tap drill size			recommended seating torques – Pound-inches								
				regular and LOC-WEL screws			self-locking with NYLOK					
rad.	size	UNC	UNF	min. screw length	alloy steel	stain-less	min. screw length	alloy steel	stain-less	min. screw length	alloy steel	stain-less
.047	#0	....	1.25mm	3/32	.5	.4	3/32	.4	.3	1/8	.5	.4
.055	#1	1.5mm	1.5mm	3/32	1.5	1.2	1/8	1.2	1.0	5/32	1.5	1.2
.062	#2	#50	1.85mm	3/32	1.5	1.2	1/8	1.2	1.0	5/32	1.5	1.2
.078	#3	#46	2.1mm	3/32	5	4	3/32-1/4	4	3	5/32	5	4
.084	#4	2.3mm	#42	3/32	5	4	3/32-1/4	4	3	5/32	5	4
.093	#5	#37	#37	3/32	9	7	1/4	7	6	1/4	9	7
.109	#6	#33	#32	1/8	9	7	3/16	7	6	1/4	9	7
.125	#8	#29	3.5mm	1/8	20	16	1/4	16	13	5/16	20	16
.141	#10	#24	#20	3/32	33	26	1/4-5/16	28	22	3/8	33	26
.188	1/4	#6	5.5mm	3/16	87	70	1/4-5/16	52	42	1/2	87	70
.234	5/16	G	I	1/4	165	130	1/4-5/16	90	72	5/8	165	130
.281	3/8	O	8.6mm	5/16	290	230	3/8-1/2	200	160	3/4	290	230
.328	5/16	9.4mm	33/64	3/8	430	340	5/16-3/8	300	240	1/2	430	340
.375	1/2	27/64	11.5mm	1/2	620	500	1/2-3/4	500	400	5/8	620	500
.422	5/16	31/64	1/2	1/2	620	500	1/2-3/4	500	400	5/8	620	500
.468	3/8	17/32	14.5mm	5/16	1,225	980	3/8-1/2	980	780	1	1,225	980
.562	3/8	21/32	17.5mm	3/8	2,125	1,700	3/4-1 1/4	1,700	1,360	1 1/4	2,125	1,700
.656	1/2	49/64	20.5mm	3/4	5,000	4,000	3/4-1 1/4	3,650	2,920	1 1/4	5,000	4,000
.750	1	7/8	23.5	7/8	7,000	5,600	7/8-1 1/4	5,200	4,160	1 1/2	7,000	5,600
.844	1 1/8	25mm	1 1/64	1	7,000	5,600	....	....	....	....	....	....
.938	1 1/4	1 1/4	1 11/64	1 1/8	9,600	7,700	....	....	....	....	....	....
1.032	1 3/8	1 1/2	1 1/64	1 1/4	9,600	7,700	....	....	....	....	....	....
1.125	1 1/2	34mm	36mm	1 1/4	11,320	9,100	....	....	....	....	....	....

Note: Materials: High grade alloy steel, austenitic stainless steel.
Hardness: Rc 45-53 for alloy steel grades. Thread class: 3A.

Figure 14.11 Set-screw point types.

forming plastics). Head styles of the various machine screws are shown in Fig. 14.14.

14.2 Thread Systems: American Standard and Metric (60° V)

The international standard screw threads consist of the unified inch series and the metric series. The metric series is standardized into the M and MJ profiles. The unified series is designated as UN (unified national). Another unified profile is designated as UNR, which has a rounded root on the external thread. The metric profile MJ also has a rounded root on the external thread and a larger

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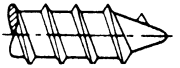
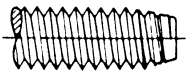
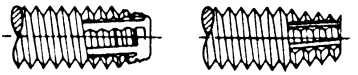
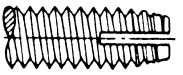
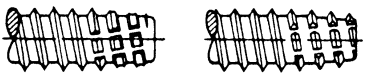
Type	ANSI Standard
	AB
 Not Recommended-Use type AB	A
	B
	BP
	C
	D
	F
	G
	T
	BF
	BT
	U

Figure 14.12 Self-tapping and thread-forming screw types.

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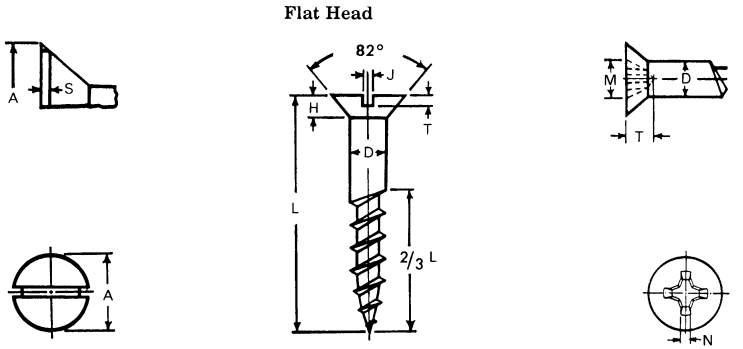

SLOTTED **PHILLIPS**

Nominal Size	D	A			B	H		J		T			D	M		T	N	
	Basic Diameter of Screw	Head Diameter			Flat on Min Screw	Height of Head		Width of Slot		Depth of Slot		Number Threads per Inch	Basic Diameter of Screw	Diameter of Recess		Depth of Recess	Width of Recess	Driver Size
		Max Sharp	Min Sharp	Absolute Min with Max B		Max	Min	Max	Min	Max	Min			Max	Min	Max	Min	
0	0.060	0.119	0.105	0.099	0.002	0.035	0.026	0.023	0.016	0.015	0.010	32	0.060	0.069	0.056	0.043	0.014	0
1	0.073	0.146	0.130	0.123	0.003	0.043	0.033	0.026	0.019	0.019	0.012	28	0.073	0.077	0.064	0.051	0.015	0
2	0.086	0.172	0.156	0.147	0.003	0.051	0.040	0.031	0.023	0.023	0.015	26	0.086	0.102	0.089	0.063	0.017	1
3	0.099	0.199	0.181	0.171	0.004	0.059	0.048	0.035	0.027	0.027	0.017	24	0.099	0.107	0.094	0.068	0.018	1
4	0.112	0.225	0.207	0.195	0.004	0.067	0.055	0.039	0.031	0.030	0.020	22	0.112	0.128	0.115	0.089	0.018	1
5	0.125	0.252	0.232	0.220	0.005	0.075	0.062	0.043	0.035	0.034	0.022	20	0.125	0.154	0.141	0.086	0.027	2
6	0.138	0.279	0.257	0.244	0.005	0.083	0.069	0.048	0.039	0.038	0.024	18	0.138	0.174	0.161	0.106	0.029	2
7	0.151	0.305	0.283	0.268	0.005	0.091	0.076	0.048	0.039	0.041	0.027	16	0.151	0.189	0.176	0.121	0.031	2
8	0.164	0.332	0.308	0.292	0.006	0.100	0.084	0.054	0.045	0.045	0.029	15	0.164	0.204	0.191	0.136	0.032	2
9	0.177	0.358	0.334	0.316	0.006	0.108	0.091	0.054	0.045	0.049	0.032	14	0.177	0.214	0.201	0.146	0.033	2
10	0.190	0.385	0.359	0.340	0.007	0.116	0.098	0.060	0.050	0.053	0.034	13	0.190	0.258	0.245	0.146	0.034	3
12	0.216	0.438	0.410	0.389	0.008	0.132	0.112	0.067	0.056	0.060	0.039	11	0.216	0.283	0.270	0.171	0.036	3
14	0.242	0.491	0.461	0.437	0.009	0.148	0.127	0.075	0.064	0.068	0.044	10	0.242	0.303	0.290	0.191	0.039	3
16	0.268	0.544	0.512	0.485	0.010	0.164	0.141	0.075	0.064	0.075	0.049	9	0.268	0.327	0.314	0.216	0.045	3
18	0.294	0.597	0.563	0.534	0.011	0.180	0.155	0.084	0.072	0.083	0.054	8	0.294	0.378	0.365	0.230	0.062	4
20	0.320	0.650	0.614	0.582	0.012	0.196	0.170	0.084	0.072	0.090	0.059	8	0.320	0.393	0.380	0.245	0.065	4
24	0.372	0.756	0.716	0.679	0.013	0.228	0.198	0.094	0.081	0.105	0.069	7	0.372	0.424	0.411	0.276	0.069	4

Figure 14.13 American standard wood screw dimensions.

minor diameter of both the internal and external threads. Both the UNR and MJ profiles are used for applications requiring high fatigue strength; they are also employed in aerospace applications.

A constant-pitch unified series is also standardized and consists of 4, 6, 8, 12, 16, 20, 28, and 32 threads per inch. These are used for sizes over 1 in in diameter, and 8UN, 12UN, and 16UN are the

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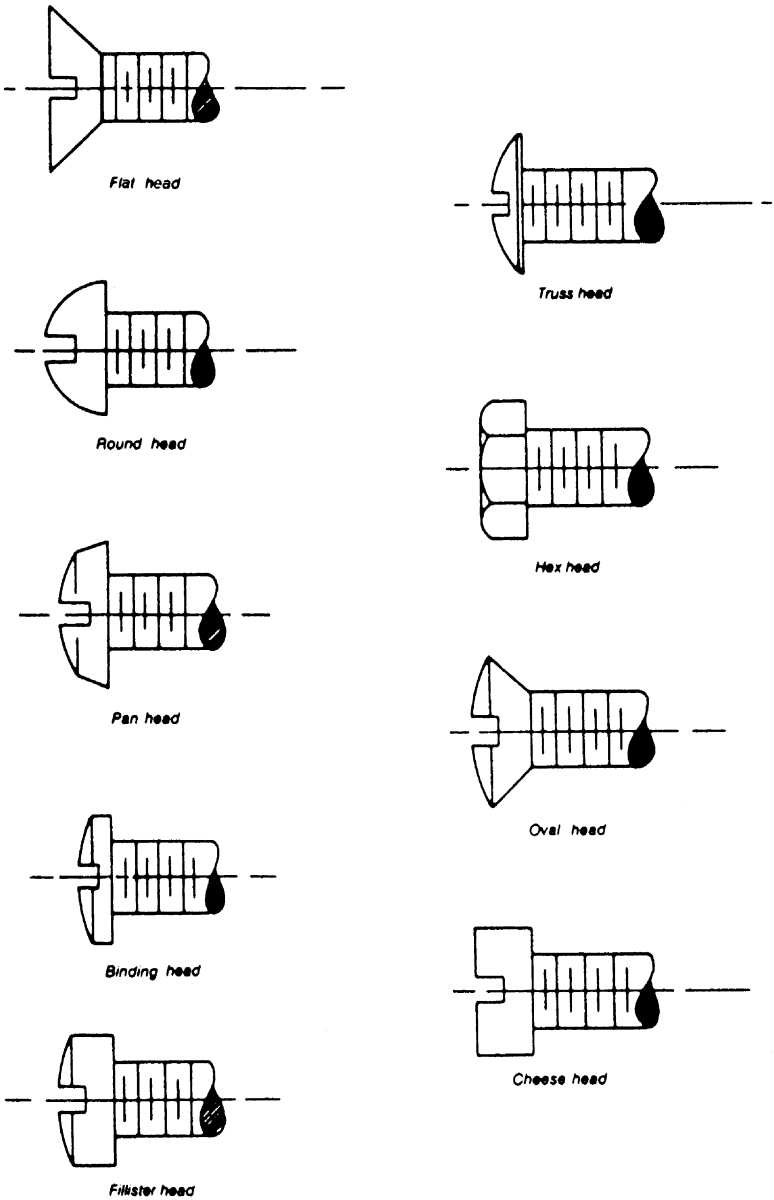

Figure 14.14 Head styles of standard machine screws.

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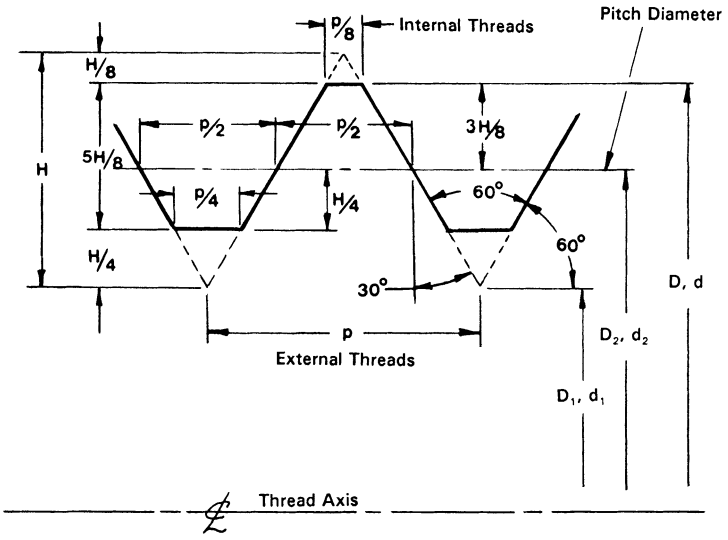

Basic Thread Profile for Unified (UN) and Metric (M) Threads (ISO 68)

$D,(d)$ = basic major diameter of internal (external) thread
$D_1,(d_1)$ = basic minor diameter of internal (external) thread
$D_2,(d_2)$ = basic pitch diameter of internal (external) thread
p = pitch
$H = 0.5\sqrt{3}\,p$

Figure 14.15 Basic thread profiles (unified and metric).

preferred pitches. Figure 14.15 shows that both the unified and metric M series use the same profile geometry. The other common screw thread systems include the Acme, stub Acme, Whitworth, buttress, and others.

The unified threads are further classified as UN A for external threads and UN B for internal threads. The UN series contains three fit classes, 1A, 2A, and 3A for external threads and 1B, 2B, and 3B for internal threads. A typical engineering drawing callout for a coarse external class 2 thread in ¼-20 size would be

0.250-20UNC-2A

A ¼-20 size class 2 tapped hole would be shown as

0.250-20UNC-2B

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Thread fit classes. Unified thread series and interference-fit threads.

Unified thread series

1A: External, loose fit for easy assembly and noncritical uses

2A: External, general applications where plating may be applied

3A: External, tight fit used for great accuracy; no plating allowance provided

1B: Internal, loose fit for easy assembly and noncritical uses

2B: Internal, general applications where plating may be applied

3B: Internal, tight fit used for great accuracy; no plating allowance provided

Class 5 interference-fit threads

Class 5 external

NC5 HF: For driving in hard ferrous materials over 160 Brinell hardness number (BHN)

NC5 CSF: For driving in copper alloys and soft ferrous materials under 160 BHN

NC5 ONF: For other nonferrous materials, any hardness

Class 5 internal

NC5 IF: Entire ferrous material range

NC5 INF: Entire nonferrous material range

Interference-fit threads are used commonly on threaded studs to ensure a tight, vibration-resistant fit. The internal thread of a class 5 interference-fit application should be lubricated for best results when torquing the stud or externally threaded part into the class 5 fit tapped hole.

14.2.1 Unified and metric thread data

Unified national tap drill sizes. You may calculate the tap drill diameter for 75 and 100 percent thread for the unified and metric M profile series using the following equations. For unified national threads,

$$D_{td} = D_m - \frac{0.947}{n} \qquad \text{(Tap drill diameter for 75 percent thread)}$$

$$D_{td} = D_m - \frac{1.299}{n} \qquad \text{(Tap drill diameter for 100 percent thread)}$$

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For metric threads, M profile,

$$D_d = D_M - \frac{(\%T)(p)}{76.98}$$

$$\%T = \frac{76.98}{p}(D_M - D_d)$$

In the preceding equations, symbolism is as follows: For unified threads,

D_{td} = diameter of tap drill, in
D_m = major diameter of external thread or tap diameter, in
n = number of threads per inch

For metric threads,

D_d = drilled hole diameter, mm
D_M = basic major diameter, mm
$\%T$ = percent of thread (i.e., 70 percent = 0.70, etc.)
p = pitch of thread, mm

Note: Recommended percent of thread is usually taken as 70 to 75 percent for a general class 2 type fit, which allows for electroplatings such as zinc, cadmium, chrome, nickel, etc.

Unified national coarse (UNC) screw thread data are presented in Fig. 14.16. Unified national fine (UNF) screw thread data are

Screw Thread Data, Unified National Coarse, (UNC)

Thread	Tap Drill	Decimal, in.	Stress Area Sq. inches	Basic Pitch Diameter, inches
#1-64	#53	0.0595	0.0026	0.0629
#2-56	#50	0.0700	0.0037	0.0744
#3-48	#47	0.0785	0.0048	0.0855
#4-40	#43	0.0890	0.0060	0.0958
#5-40	#38	0.1015	0.0080	0.1088
#6-32	#36	0.1065	0.0090	0.1177
#8-32	#29	0.1360	0.0140	0.1437
#10-24	#25	0.1495	0.0175	0.1629
¼-20	#7	0.2010	0.0318	0.2175
5/16-18	F	0.2570	0.0524	0.2764
3/8-16	5/16	0.3125	0.0775	0.3344
7/16-14	T	0.3580	0.1063	0.3911
½-13	27/64	0.4219	0.1419	0.4500
9/16-12	31/64	0.4844	0.1820	0.5084
5/8-11	17/32	0.5312	0.2260	0.5660
¾-10	41/64	0.6406	0.3340	0.6850
7/8-9	49/64	0.7656	0.4620	0.8028
1-8	7/8	0.8750	0.6060	0.9188

Figure 14.16 Screw thread data (UNC).

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Screw Thread Data, Unified National Fine, (UNF)

Thread	Tap Drill	Decimal, in.	Stress Area, Sq. inches	Basic Pitch Diameter, inches
#0-80	3/64	0.0469	0.0018	0.0519
#1-72	#53	0.0595	0.0027	0.0640
#2-64	#50	0.0700	0.0039	0.0759
#3-56	#45	0.0820	0.0052	0.0874
#4-48	#42	0.0935	0.0066	0.0985
#5-44	#37	0.1040	0.0083	0.1102
#6-40	#33	0.1130	0.0102	0.1218
#8-36	#29	0.1360	0.0147	0.1460
#10-32	#21	0.1590	0.0200	0.1697
¼-28	#3	0.2130	0.0364	0.22268
5/16-24	I	0.2720	0.0580	0.2854
3/8-24	Q	0.3320	0.0878	0.3479
7/16-20	25/64	0.3906	0.1187	0.4050
½-20	29/64	0.4531	0.1599	0.4675
9/16-18	33/64	0.5156	0.2030	0.5264
5/8-18	9/16	0.5625	0.2560	0.5889
¾-16	11/16	0.6875	0.3730	0.7094
7/8-14	13/16	0.8125	0.5090	0.8286
1-12	29/32	0.9063	0.6630	0.9459

Figure 14.17 Screw thread data (UNF).

presented in Fig. 14.17. Metric M profile thread data are presented in Fig. 14.18. American national drill sizes are shown in Fig. 14.19 and metric sizes in Fig. 14.20. Both number and letter size drills are indicated with their decimal equivalents.

The standard limits of size for both American and unified national series screw threads are fully covered in Table 14.1. The four sections of the table are extracted from National Bureau of Standards Handbook H-28 and are in general agreement with current American National Standards Institute (ANSI) standards. The table covers or includes sizes 0-80 through 3-16UN.

Engagement of threads. The length of engagement of a stud end or bolt end E can be stated in terms of the major diameter D of the thread. In general,

- For a steel stud in cast iron or steel, $E = 1.50D$.
- For a steel stud in hardened steel or high-strength bronze, $E = D$.
- For a steel stud in aluminum or magnesium alloys subjected to shock loads, $E = 2.00D + 0.062$.
- For a steel stud as above subjected to normal loads, $E = 1.50D + 0.062$.

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Metric Thread Data, M Profile, Internal and External

Thread Designation Dia. X Pitch (Millimeters)	Tap Drill, mm	Pitch Dia. 6H, Internal, mm	Pitch Dia. 6G, External, mm
M1.6 x 0.35	1.25	1.373	1.291
M2 x 0.4	1.60	1.740	1.654
M2.5 x 0.45	2.05	2.208	2.117
M3 x 0.5	2.50	2.675	2.580
M3.5 x 0.6	2.90	3.110	3.004
M4 x 0.7	3.30	3.545	3.433
M5 x 0.8	4.20	4.480	4.361
M6 x 1	5.00	5.350	5.212
M8 x 1.25	6.70	7.188	7.042
M8 x 1	7.00	7.350	7.212
M10 x 1.5	8.50	9.026	8.862
M10 x 1.25	8.70	9.188	9.042
M10 x 0.75	------	9.513	9.391
M12 x 1.75	10.20	10.863	10.679
M12 x 1.5	------	11.026	10.854
M12 x 1.25	10.80	11.188	11.028
M12 x 1	------	11.350	11.206
M14 x 2	12.00	12.701	12.503
M14 x 1.5	12.50	13.026	12.854
M15 x 1	------	14.350	14.206
M16 x 2	14.00	14.701	14.503
M16 x 1.5	14.50	15.026	14.854
M17 x 1	------	16.350	16.206
M18 x 1.5	16.50	17.026	16.854
M20 x 2.5	17.50	18.376	18.164
M20 x 1.5	18.50	19.026	18.854
M20 x 1	------	19.350	19.206
M22 x 2.5	19.50	20.376	20.164
M22 x 1.5	20.50	21.026	20.854
M24 x 3	21.00	22.051	21.803
M24 x 2	22.00	22.701	22.493
M25 x 1.5	------	24.026	23.854

Figure 14.18 Metric thread data.

Load to break a threaded section. For screws or bolts,

$$P_b = SA_{ts}$$

where P_b = load to break the screw or bolt, pounds-force (lbf)
S = ultimate tensile strength of screw or bolt material, lb/in^2
A_{ts} = tensile stress area of screw or bolt thread, in^2

Tensile stress area calculation. The tensile stress area A_{ts} of screws and bolts is derived from

$$A_{ts} = \frac{\pi}{4}\left(D - \frac{0.9743}{n}\right)^2 \qquad \text{for inch-series threads}$$

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where A_{ts} = tensile stress area of screw or bolt thread, in^2
D = basic major diameter of thread, in
n = number of threads per inch

Note: You may select the stress areas for unified bolts or screws by using Figs. 14.16 and 14.17, whereas the metric stress areas may be derived by converting millimeters to inches for each metric fastener and using the preceding equation.

(Text continued on page 888.)

DRILL NO.	DECIMAL	DRILL NO.	DECIMAL	DRILL NO.	DECIMAL
97	0.0059	56	0.0465	15	0.180
96	0.0063	55	0.052	14	0.182
95	0.0067	54	0.055	13	0.185
94	0.0071	53	0.0595	12	0.189
93	0.0075	52	0.0635	11	0.191
92	0.0079	51	0.067	10	0.1935
91	0.0083	50	0.070	9	0.196
90	0.0087	49	0.073	8	0.199
89	0.0091	48	0.076	7	0.201
88	0.0095	47	0.0785	6	0.204
87	0.010	46	0.076	5	0.2055
86	0.0105	45	0.082	4	0.209
85	0.011	44	0.086	3	0.213
84	0.0115	43	0.089	2	0.221
83	0.012	42	0.0935	1	0.228
82	0.0125	41	0.096	A	0.234
81	0.013	40	0.098	B	0.238
80	0.0135	39	0.0995	C	0.242
79	0.0145	38	0.1015	D	0.246
78	0.016	37	0.104	E	0.250
77	0.018	36	0.1065	F	0.257
76	0.020	35	0.110	G	0.261
75	0.021	34	0.111	H	0.266
74	0.0225	33	0.113	I	0.272
73	0.024	32	0.116	J	0.277
72	0.025	31	0.120	K	0.281
71	0.026	30	0.1285	L	0.290
70	0.028	29	0.136	M	0.295
69	0.0292	28	0.1405	N	0.302
68	0.031	27	0.144	O	0.316
67	0.032	26	0.147	P	0.323
66	0.033	25	0.1495	Q	0.332
65	0.035	24	0.152	R	0.339
64	0.036	23	0.154	S	0.348
63	0.037	22	0.157	T	0.358
62	0.038	21	0.159	U	0.368
61	0.039	20	0.161	V	0.377
60	0.040	19	0.166	W	0.386
59	0.041	18	0.1695	X	0.397
58	0.042	17	0.173	Y	0.404
57	0.043	16	0.177	Z	0.413

Figure 14.19 American national standard drill sizes.

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Metric Drill Sizes

Drill	Decimal	Drill	Decimal	Drill	Decimal	Drill	Decimal	Drill	Decimal	Drill	Decimal
.35mm	.0138	1.75mm	.0650	3.70mm	.1457	6.40mm	.2520	9.00mm	.3543	17.00mm	.6693
.38mm	.0150	1.80mm	.0709	3.75mm	.1477	6.50mm	.2559	9.10mm	.3583	17.50mm	.6890
.40mm	.0157	1.85mm	.0728	3.80mm	.1496	6.60mm	.2598	9.20mm	.3622	18.00mm	.7087
.42mm	.0165	1.90mm	.0748	3.90mm	.1535	6.70mm	.2638	9.25mm	.3642	18.50mm	.7283
.45mm	.0177	1.95mm	.0768	4.00mm	.1575	6.75mm	.2658	9.30mm	.3661	19.00mm	.7480
.48mm	.0189	2.00mm	.0787	4.10mm	.1614	6.80mm	.2677	9.40mm	.3701	19.50mm	.7677
.50mm	.0197	2.05mm	.0807	4.20mm	.1654	6.90mm	.2716	9.50mm	.3740	20.00mm	.7874
.55mm	.0217	2.10mm	.0827	4.25mm	.1674	7.00mm	.2756	9.60mm	.3780	20.50mm	.8071
.60mm	.0236	2.15mm	.0846	4.50mm	.1771	7.10mm	.2795	9.70mm	.3819	21.00mm	.8268
.65mm	.0256	2.20mm	.0866	4.60mm	.1811	7.20mm	.2835	9.75mm	.3839	21.50mm	.8465
.70mm	.0276	2.25mm	.0886	4.70mm	.1850	7.25mm	.2855	9.80mm	.3558	22.00mm	.8661
.75mm	.0295	2.30mm	.0905	4.75mm	.1870	7.30mm	.2874	9.90mm	.3898	22.50mm	.8858
.80mm	.0315	2.35mm	.0925	4.80mm	.1890	7.40mm	.2913	10.00mm	.3937	23.00mm	.9055
.85mm	.0335	2.40mm	.0945	4.90mm	.1929	7.50mm	.2953	10.20mm	.4016	23.50mm	.9252
.90mm	.0354	2.45mm	.0965	5.00mm	.1968	7.60mm	.2992	10.50mm	.4134	24.00mm	.9449
.95mm	.0374	2.50mm	.0984	5.10mm	.2008	7.70mm	.3031	10.80mm	.4252	24.50mm	.9646
1.00mm	.0394	2.55mm	.1004	5.20mm	.2047	7.75mm	.3051	11.00mm	.4330	25.00mm	.9843
1.05mm	.0413	2.60mm	.1024	5.25mm	.2067	7.80mm	.3071	11.20mm	.4409		
1.10mm	.0433	2.65mm	.1043	5.30mm	.2087	7.90mm	.3110	11.50mm	.4528		
1.15mm	.0453	2.70mm	.1063	5.40mm	.2126	8.00mm	.3150	11.80mm	.4646	+1.00mm increments	
1.20mm	.0472	2.75mm	.1083	5.50mm	.2165	8.10mm	.3189	12.00mm	.4724	up to 48mm.	
1.25mm	.0492	2.80mm	.1102	5.60mm	.2205	8.20mm	.3228	12.20mm	.4803		
1.30mm	.0512	2.90mm	.1142	5.70mm	.2244	8.25mm	.3248	12.50mm	.4921	+5.00mm increments	
1.35mm	.0531	3.00mm	.1181	5.75mm	.2264	8.30mm	.3268	13.00mm	.5118	from 50mm up to	
1.40mm	.0551	3.10mm	.1220	5.80mm	.2283	8.40mm	.3307	13.50mm	.5315	105mm.	
1.45mm	.0571	3.20mm	.1260	5.90mm	.2323	8.50mm	.3346	14.00mm	.5512		
1.50mm	.0591	3.25mm	.1280	6.00mm	.2362	8.60mm	.3386	14.50mm	.5709		
1.55mm	.0610	3.30mm	.1299	6.10mm	.2401	8.70mm	.3425	15.00mm	.5906		
1.60mm	.0629	3.40mm	.1339	6.20mm	.2441	8.75mm	.3445	15.50mm	.6102		
1.65mm	.0650	3.50mm	.1378	6.25mm	.2461	8.80mm	.3465	16.00mm	.6299		
1.70mm	.0669	3.60mm	.1417	6.30mm	.2480	8.90mm	.3504	16.50mm	6496		

Figure 14.20 Metric drill sizes.

TABLE 14.1 Standard Limits of Size: Unified and American Screw Threads

Nominal size and threads per inch	Series designation	External									Internal						
				Major diameter limits, in			Pitch diameter limits, in			Minor diameter, in		Minor diameter limits, in		Pitch diameter limits, in			Major diameter, in
		Class	Allowance, in	Max*	Min	Min†	Max*	Min	Tolerance		Class	Min	Max	Min	Max	Tolerance	Min
No. 0–80 to ½–13																	
0–80	NF	2A	0.0005	0.0595	0.0563		0.0514	0.0496	0.0018	0.0442	2B	0.0465	0.0514	0.0519	0.0542	0.0023	0.0600
		3A	0.0000	0.0600	0.0568		0.0519	0.0506	0.0013	0.0447	3B	0.0465	0.0514	0.0519	0.0536	0.0017	0.0600
1–64	NC	2A	0.0006	0.0724	0.0686		0.0623	0.0603	0.0020	0.0532	2B	0.0561	0.0623	0.0629	0.0655	0.0026	0.0730
		3A	0.0000	0.0730	0.0692		0.0629	0.0614	0.0015	0.0538	3B	0.0561	0.0623	0.0629	0.0648	0.0019	0.0730
1–72	NF	2A	0.0006	0.0724	0.0689		0.0634	0.0615	0.0019	0.0554	2B	0.0580	0.0635	0.0640	0.0665	0.0025	0.0730
		3A	0.0000	0.0730	0.0695		0.0640	0.0626	0.0014	0.0560	3B	0.0580	0.0635	0.0640	0.0659	0.0019	0.0730
2–56	NC	2A	0.0006	0.0854	0.0813		0.0738	0.0717	0.0021	0.0635	2B	0.0667	0.0737	0.0744	0.0772	0.0028	0.0860
		3A	0.0000	0.0860	0.0819		0.0744	0.0728	0.0016	0.0641	3B	0.0667	0.0737	0.0744	0.0765	0.0021	0.0860
2–64	NF	2A	0.0006	0.0854	0.0816		0.0753	0.0733	0.0020	0.0662	2B	0.0691	0.0753	0.0759	0.0786	0.0027	0.0860
		3A	0.0000	0.0860	0.0822		0.0759	0.0744	0.0015	0.0668	3B	0.0691	0.0753	0.0759	0.0779	0.0020	0.0860
3–48	NC	2A	0.0007	0.0983	0.0938		0.0848	0.0825	0.0023	0.0727	2B	0.0764	0.0845	0.0855	0.0885	0.0030	0.0990
		3A	0.0000	0.0990	0.0945		0.0855	0.0838	0.0017	0.0734	3B	0.0764	0.0845	0.0855	0.0877	0.0022	0.0990
3–56	NF	2A	0.0007	0.0983	0.0942		0.0867	0.0845	0.0022	0.0764	2B	0.0797	0.0865	0.0874	0.0902	0.0028	0.0990
		3A	0.0000	0.0990	0.0949		0.0874	0.0858	0.0016	0.0771	3B	0.0797	0.0865	0.0874	0.0895	0.0021	0.0990
4–40	NC	2A	0.0008	0.1112	0.1061		0.0950	0.0925	0.0025	0.0805	2B	0.0849	0.0939	0.0958	0.0991	0.0033	0.1120
		3A	0.0000	0.1120	0.1069		0.0958	0.0939	0.0019	0.0813	3B	0.0849	0.0939	0.0958	0.0982	0.0024	0.1120
4–48	NF	2A	0.0007	0.1113	0.1068		0.0978	0.0954	0.0024	0.0857	2B	0.0894	0.0968	0.0985	0.1016	0.0031	0.1120
		3A	0.0000	0.1120	0.1075		0.0985	0.0967	0.0018	0.0864	3B	0.0894	0.0968	0.0985	0.1008	0.0023	0.1120
5–40	NC	2A	0.0008	0.1242	0.1191		0.1080	0.1054	0.0026	0.0935	2B	0.0979	0.1062	0.1088	0.1121	0.0033	0.1250
		3A	0.0000	0.1250	0.1199		0.1088	0.1069	0.0019	0.0943	3B	0.0979	0.1062	0.1088	0.1113	0.0025	0.1250
5–44	NF	2A	0.0007	0.1243	0.1195		0.1095	0.1070	0.0025	0.0964	2B	0.1004	0.1079	0.1102	0.1134	0.0032	0.1250
		3A	0.0000	0.1250	0.1202		0.1102	0.1083	0.0019	0.0971	3B	0.1004	0.1079	0.1102	0.1126	0.0024	0.1250
6–32	NC	2A	0.0008	0.1372	0.1312		0.1169	0.1141	0.0028	0.0989	2B	0.104	0.114	0.1177	0.1214	0.0037	0.1380
		3A	0.0000	0.1380	0.1320		0.1177	0.1156	0.0021	0.0997	3B	0.1040	0.1140	0.1177	0.1204	0.0027	0.1380
6–40	NF	2A	0.0008	0.1372	0.1321		0.1210	0.1184	0.0026	0.1065	2B	0.111	0.119	0.1218	0.1252	0.0034	0.1380
		3A	0.0000	0.1380	0.1329		0.1218	0.1198	0.0020	0.1073	3B	0.1110	0.1186	0.1218	0.1243	0.0025	0.1380

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8–32	NC	2A	0.0009	0.1631	0.1571		0.1428	0.1399	0.0029	0.1248	2B	0.130	0.139	0.1437	0.1475	0.0038	0.1640
		3A	0.0000	0.1640	0.1580		0.1437	0.1415	0.0022	0.1257	3B	0.1300	0.1389	0.1437	0.1465	0.0028	0.1640
8–36	NF	2A	0.0008	0.1632	0.1577		0.1452	0.1424	0.0028	0.1291	2B	0.134	0.142	0.1460	0.1496	0.0036	0.1640
		3A	0.0000	0.1640	0.1585		0.1460	0.1439	0.0021	0.1299	3B	0.1340	0.1416	0.1460	0.1487	0.0027	0.1640
10–24	NC	2A	0.0010	0.1890	0.1818		0.1619	0.1586	0.0033	0.1379	2B	0.145	0.156	0.1629	0.1672	0.0043	0.1900
		3A	0.0000	0.1900	0.1828		0.1629	0.1604	0.0025	0.1389	3B	0.1450	0.1555	0.1629	0.1661	0.0032	0.1900
10–32	NF	2A	0.0009	0.1891	0.1831		0.1688	0.1658	0.0030	0.1508	2B	0.156	0.164	0.1697	0.1736	0.0039	0.1900
		3A	0.0000	0.1900	0.1840		0.1697	0.1674	0.0023	0.1517	3B	0.1560	0.1641	0.1697	0.1726	0.0029	0.1900
12–24	NC	2A	0.0010	0.2150	0.2078		0.1879	0.1845	0.0034	0.1639	2B	0.171	0.181	0.1889	0.1933	0.0044	0.2160
		3A	0.0000	0.2160	0.2088		0.1889	0.1863	0.0026	0.1649	3B	0.1710	0.1807	0.1889	0.1922	0.0033	0.2160
12–28	NF	2A	0.0010	0.2150	0.2085		0.1918	0.1886	0.0032	0.1712	2B	0.177	0.186	0.1928	0.1970	0.0042	0.2160
		3A	0.0000	0.2160	0.2095		0.1928	0.1904	0.0024	0.1722	3B	0.1770	0.1857	0.1928	0.1959	0.0031	0.2160
12–32	NEF	2A	0.0009	0.2151	0.2091		0.1948	0.1917	0.0031	0.1768	2B	0.182	0.190	0.1957	0.1998	0.0041	0.2160
		3A	0.0000	0.2160	0.2100		0.1957	0.1933	0.0024	0.1777	3B	0.1820	0.1895	0.1957	0.1988	0.0031	0.2160
¼–20	UNC	1A	0.0011	0.2489	0.2367	0.2367	0.2164	0.2108	0.0056	0.1876	1B	0.196	0.207	0.2175	0.2248	0.0073	0.2500
		2A	0.0011	0.2489	0.2408		0.2164	0.2127	0.0037	0.1876	2B	0.196	0.207	0.2175	0.2223	0.0048	0.2500
		3A	0.0000	0.2500	0.2419		0.2175	0.2147	0.0028	0.1887	3B	0.1960	0.2067	0.2175	0.2211	0.0036	0.2500
¼–28	UNF	1A	0.0010	0.2490	0.2392		0.2258	0.2208	0.0050	0.2052	1B	0.211	0.220	0.2268	0.2333	0.0065	0.2500
		2A	0.0010	0.2490	0.2425		0.2258	0.2225	0.0033	0.2052	2B	0.211	0.220	0.2268	0.2311	0.0043	0.2500
		3A	0.0000	0.2500	0.2435		0.2268	0.2243	0.0025	0.2062	3B	0.2110	0.2190	0.2268	0.2300	0.0032	0.2500
¼–32	NEF	2A	0.0010	0.2490	0.2430		0.2287	0.2255	0.0032	0.2107	2B	0.216	0.224	0.2297	0.2339	0.0042	0.2500
		3A	0.0000	0.2500	0.2440		0.2297	0.2273	0.0024	0.2117	3B	0.2160	0.2229	0.2297	0.2328	0.0031	0.2500
⅝–18	UNC	1A	0.0012	0.3113	0.2982	0.2982	0.2752	0.2691	0.0061	0.2431	1B	0.252	0.265	0.2764	0.2843	0.0079	0.3125
		2A	0.0012	0.3113	0.3026		0.2752	0.2712	0.0040	0.2431	2B	0.252	0.265	0.2764	0.2817	0.0053	0.3125
		3A	0.0000	0.3125	0.3038		0.2764	0.2734	0.0030	0.2443	3B	0.2520	0.2630	0.2764	0.2803	0.0039	0.3125
⅝–24	UNF	1A	0.0011	0.3114	0.3006		0.2843	0.2788	0.0055	0.2603	1B	0.267	0.277	0.2854	0.2925	0.0071	0.3125
		2A	0.0011	0.3114	0.3042		0.2843	0.2806	0.0037	0.2603	2B	0.267	0.277	0.2854	0.2902	0.0048	0.3125
		3A	0.0000	0.3125	0.3053		0.2854	0.2827	0.0027	0.2614	3B	0.2670	0.2754	0.2854	0.2890	0.0036	0.3125

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TABLE 14.1 Standard Limits of Size: Unified and American Screw Threads (*Continued*)

Nominal size and threads per inch	Series designation	External									Internal						
				Major diameter limits, in			Pitch diameter limits, in			Minor diameter, in		Minor diameter limits, in		Pitch diameter limits, in			Major diameter, in
		Class	Allowance, in	Max*	Min	Min†	Max*	Min	Tolerance		Class	Min	Max	Min	Max	Tolerance	Min
No. 0–80 to ½–13																	
5/16–32	NEF	2A	0.0010	0.3115	0.3055		0.2912	0.2880	0.0032	0.2732	2B	0.279	0.286	0.2922	0.2964	0.0042	0.3125
		3A	0.0000	0.3125	0.3065		0.2922	0.2898	0.0024	0.2742	3B	0.2790	0.2847	0.2922	0.2953	0.0031	0.3125
3/8–16	UNC	1A	0.0013	0.3737	0.3595		0.3331	0.3266	0.0065	0.2970	1B	0.307	0.321	0.3344	0.3429	0.0085	0.3750
		2A	0.0013	0.3737	0.3643	0.3595	0.3331	0.3287	0.0044	0.2970	2B	0.307	0.321	0.3344	0.3401	0.0057	0.3750
		3A	0.0000	0.3750	0.3656		0.3344	0.3311	0.0033	0.2983	3B	0.3070	0.3182	0.3344	0.3387	0.0043	0.3750
3/8–24	UNF	1A	0.0011	0.3739	0.3631		0.3468	0.3411	0.0057	0.3228	1B	0.330	0.340	0.3479	0.2553	0.0074	0.3750
		2A	0.0011	0.3739	0.3667		0.3468	0.3430	0.0038	0.3228	2B	0.330	0.340	0.3479	0.3528	0.0049	0.3750
		3A	0.0000	0.3750	0.3678		0.3479	0.3450	0.0029	0.3239	3B	0.3300	0.3372	0.3479	0.3516	0.0037	0.3750
3/8–32	NEF	2A	0.0010	0.3740	0.3680		0.3537	0.3503	0.0034	0.3357	2B	0.341	0.349	0.3547	0.3591	0.0044	0.3750
		3A	0.0000	0.3750	0.3690		0.3547	0.3522	0.0025	0.3367	3B	0.3410	0.3469	0.3547	0.3580	0.0033	0.3750
7/16–14	UNC	1A	0.0014	0.4361	0.4206		0.3897	0.3826	0.0071	0.3485	1B	0.360	0.376	0.3911	0.4003	0.0092	0.4375
		2A	0.0014	0.4361	0.4258	0.4206	0.3897	0.3850	0.0047	0.3485	2B	0.360	0.376	0.3911	0.3972	0.0061	0.4375
		3A	0.0000	0.4375	0.4272		0.3911	0.3876	0.0035	0.3499	3B	0.3600	0.3717	0.3911	0.3957	0.0046	0.4375
7/16–20	UNF	1A	0.0013	0.4362	0.4240		0.4037	0.3975	0.0062	0.3749	1B	0.383	0.395	0.4050	0.4131	0.0081	0.4375
		2A	0.0013	0.4362	0.4281		0.4037	0.3995	0.0042	0.3749	2B	0.383	0.395	0.4050	0.4104	0.0054	0.4375
		3A	0.0000	0.4375	0.4294		0.4050	0.4019	0.0031	0.3762	3B	0.3830	0.3916	0.4050	0.4091	0.0041	0.4375
7/16–28	UNEF	2A	0.0011	0.4364	0.4299		0.4132	0.4096	0.0036	0.3926	2B	0.399	0.407	0.4143	0.4189	0.0046	0.4375
		3A	0.0000	0.4375	0.4310		0.4143	0.4116	0.0027	0.3937	3B	0.3990	0.4051	0.4143	0.4178	0.0035	0.4375
1/2–12	N	2A	0.0016	0.4984	0.4870		0.4443	0.4389	0.0054	0.3962	2B	0.410	0.428	0.4459	0.4529	0.0070	0.5000
		3A	0.0000	0.5000	0.4886		0.4439	0.4419	0.0040	0.3978	3B	0.4100	0.4223	0.4459	0.4511	0.0052	0.5000
½–13	UNC	1A	0.0015	0.4985	0.4822		0.4485	0.4411	0.0074	0.4041	1B	0.417	0.434	0.4500	0.4597	0.0097	0.5000
		2A	0.0015	0.4985	0.4876	0.4822	0.4485	0.4435	0.0050	0.4041	2B	0.417	0.434	0.4500	0.4565	0.0065	0.5000
		3A	0.0000	0.5000	0.4891		0.4500	0.4463	0.0037	0.4056	3B	0.4170	0.4284	0.4500	0.4548	0.0048	0.5000

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½–20 to 1½–12

½–20	UNF	1A	0.0013	0.4987	0.4865		0.4662	0.4598	0.0064	0.4374	1B	0.446	0.457	0.4675	0.4759	0.0084	0.5000
		2A	0.0013	0.4987	0.4906		0.4662	0.4619	0.0043	0.4374	2B	0.446	0.457	0.4675	0.4731	0.0056	0.5000
		3A	0.0000	0.5000	0.4919		0.4675	0.4643	0.0032	0.4387	3B	0.4460	0.4537	0.4675	0.4717	0.0042	0.5000
½–28	UNEF	2A	0.0011	0.4989	0.4924		0.4757	0.4720	0.0037	0.4551	2B	0.461	0.470	0.4768	0.4816	0.0048	0.5000
		3A	0.0000	0.5000	0.4935		0.4768	0.4740	0.0028	0.4562	3B	0.4610	0.4676	0.4768	0.4804	0.0036	0.5000
9/16–12	UNC	1A	0.0016	0.5609	0.5437	0.5437	0.5068	0.4990	0.0078	0.4587	1B	0.472	0.490	0.5084	0.5186	0.0102	0.5625
		2A	0.0016	0.5609	0.5495		0.5068	0.5016	0.0052	0.4587	2B	0.472	0.490	0.5084	0.5152	0.0068	0.5625
		3A	0.0000	0.5625	0.5511		0.5084	0.5045	0.0039	0.4603	3B	0.4720	0.4843	0.5084	0.5135	0.0051	0.5625
9/16–18	UNF	1A	0.0014	0.5611	0.5480		0.5250	0.5182	0.0068	0.4929	1B	0.502	0.515	0.5264	0.5353	0.0089	0.5625
		2A	0.0014	0.5611	0.5524		0.5250	0.5205	0.0045	0.4929	2B	0.502	0.515	0.5264	0.5323	0.0059	0.5625
		3A	0.0000	0.5625	0.5538		0.5264	0.5230	0.0034	0.4943	3B	0.5020	0.5106	0.5264	0.5308	0.0044	0.5625
9/16–24	NEF	2A	0.0012	0.5613	0.5541		0.5342	0.5303	0.0039	0.5102	2B	0.517	0.527	0.5354	0.5405	0.0051	0.5625
		3A	0.0000	0.5625	0.5553		0.5354	0.5325	0.0029	0.5114	3B	0.5170	0.5244	0.5354	0.5392	0.0038	0.5625
5/8–11	UNC	1A	0.0016	0.6234	0.6052	0.6052	0.5644	0.5561	0.0083	0.5119	1B	0.527	0.546	0.5660	0.5767	0.0107	0.6250
		2A	0.0016	0.6234	0.6113		0.5644	0.5589	0.0055	0.5119	2B	0.527	0.546	0.5660	0.5732	0.0072	0.6250
		3A	0.0000	0.6250	0.6129		0.5660	0.5619	0.0041	0.5135	3B	0.5270	0.5391	0.5660	0.5714	0.0054	0.6250
5/8–12	N	2A	0.0016	0.6234	0.6120		0.5693	0.5639	0.0054	0.5212	2B	0.535	0.553	0.5709	0.5780	0.0071	0.6250
		3A	0.0000	0.6250	0.6136		0.5709	0.5668	0.0041	0.5228	3B	0.5350	0.5463	0.5709	0.5762	0.0053	0.6250
5/8–18	UNF	1A	0.0014	0.6236	0.6105		0.5875	0.5805	0.0070	0.5554	1B	0.565	0.578	0.5889	0.5980	0.0091	0.6250
		2A	0.0014	0.6236	0.6149		0.5875	0.5828	0.0047	0.5554	2B	0.565	0.578	0.5889	0.5949	0.0060	0.6250
		3A	0.0000	0.6250	0.6163		0.5889	0.5854	0.0035	0.5568	3B	0.5650	0.5730	0.5889	0.5934	0.0045	0.6250
5/8–24	NEF	2A	0.0012	0.6238	0.6166		0.5967	0.5927	0.0040	0.5727	2B	0.580	0.590	0.5979	0.6031	0.0052	0.6250
		3A	0.0000	0.6250	0.6178		0.5979	0.5949	0.0030	0.5739	3B	0.5800	0.5809	0.5979	0.6018	0.0039	0.6250
11/16–12	N	2A	0.0016	0.6859	0.6745		0.6318	0.6264	0.0054	0.5837	2B	0.597	0.615	0.6334	0.6405	0.0071	0.6875
		3A	0.0000	0.6875	0.6761		0.6334	0.6293	0.0041	0.5853	3B	0.5970	0.6085	0.6334	0.6387	0.0053	0.6875
11/16–24	NEF	2A	0.0012	0.6863	0.6791		0.6592	0.6552	0.0040	0.6352	2B	0.642	0.652	0.6604	0.6656	0.0052	0.6875
		3A	0.0000	0.6875	0.6803		0.6604	0.6574	0.0030	0.6364	3B	0.6420	0.6494	0.6604	0.6643	0.0039	0.6875
3/4–10	UNC	1A	0.0018	0.7482	0.7288	0.7288	0.6832	0.6744	0.0088	0.6255	1B	0.642	0.663	0.6850	0.6965	0.0115	0.7500
		2A	0.0018	0.7482	0.7353		0.6832	0.6773	0.0059	0.6255	2B	0.642	0.663	0.6850	0.6927	0.0077	0.7500
		3A	0.0000	0.7500	0.7371		0.6850	0.6806	0.0044	0.6273	3B	0.6420	0.6545	0.6850	0.6907	0.0057	0.7500
3/4–12	N	2A	0.0017	0.7483	0.7369		0.6942	0.6887	0.0055	0.6461	2B	0.660	0.678	0.6959	0.7031	0.0072	0.7500
		3A	0.0000	0.7500	0.7386		0.6959	0.6918	0.0041	0.6478	3B	0.6600	0.6707	0.6959	0.7013	0.0054	0.7500

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TABLE 14.1 Standard Limits of Size: Unified and American Screw Threads (*Continued*)

Nominal size and threads per inch	Series designation	External									Internal						
				Major diameter limits, in			Pitch diameter limits, in			Minor diameter, in		Minor diameter limits, in		Pitch diameter limits, in			Major diameter, in
		Class	Allowance, in	Max*	Min	Min†	Max*	Min	Tolerance		Class	Min	Max	Min	Max	Tolerance	Min
½–20 to 1⅛–12																	
¾–16	UNF	1A	0.0015	0.7485	0.7343		0.7079	0.7004	0.0075	0.6718	1B	0.682	0.696	0.7094	0.7192	0.0098	0.7500
		2A	0.0015	0.7485	0.7391		0.7079	0.7029	0.0050	0.6718	2B	0.682	0.696	0.7094	0.7159	0.0065	0.7500
		3A	0.0000	0.7500	0.7406		0.7094	0.7056	0.0038	0.6733	3B	0.6820	0.6908	0.7094	0.7143	0.0049	0.7500
¾–20	UNEF	2A	0.0013	0.7487	0.7406		0.7162	0.7118	0.0044	0.6874	2B	0.696	0.707	0.7175	0.7232	0.0057	0.7500
		3A	0.0000	0.7500	0.7419		0.7175	0.7142	0.0033	0.6887	3B	0.6960	0.7037	0.7175	0.7218	0.0043	0.7500
13/16–12	N	2A	0.0017	0.8108	0.7994		0.7567	0.7512	0.0055	0.7086	2B	0.722	0.740	0.7584	0.7656	0.0072	0.8125
		3A	0.0000	0.8125	0.8011		0.7584	0.7543	0.0041	0.7103	3B	0.7220	0.7329	0.7584	0.7638	0.0054	0.8125
13/16–16	UN	2A	0.0015	0.8110	0.8016		0.7704	0.7655	0.0049	0.7343	2B	0.745	0.759	0.7719	0.7782	0.0063	0.8125
		3A	0.0000	0.8125	0.8031		0.7719	0.7683	0.0036	0.7358	3B	0.7450	0.7533	0.7719	0.7766	0.0047	0.8125
13/16–20	UNEF	2A	0.0013	0.8112	0.8031		0.7787	0.7743	0.0044	0.7498	2B	0.758	0.770	0.7800	0.7857	0.0057	0.8125
		3A	0.0000	0.8125	0.8044		0.7800	0.7767	0.0033	0.7512	3B	0.7580	0.7662	0.7800	0.7843	0.0043	0.8125
⅞–9	UNC	1A	0.0019	0.8731	0.8523		0.8009	0.7914	0.0095	0.7368	1B	0.755	0.778	0.8028	0.8151	0.0123	0.8750
		2A	0.0019	0.8731	0.8592	0.8523	0.8009	0.7946	0.0063	0.7368	2B	0.755	0.778	0.8028	0.8110	0.0082	0.8750
		3A	0.0000	0.8750	0.8611		0.8028	0.7981	0.0047	0.7387	3B	0.7550	0.7681	0.8028	0.8089	0.0061	0.8750
⅞–12	N	2A	0.0017	0.8733	0.8619		0.8192	0.8137	0.0055	0.7711	2B	0.785	0.803	0.8209	0.8281	0.0072	0.8750
		3A	0.0000	0.8750	0.8636		0.8209	0.8168	0.0041	0.7728	3B	0.7850	0.7952	0.8209	0.8263	0.0054	0.8750
⅞–14	UNF	1A	0.0016	0.8734	0.8579		0.8270	0.8189	0.0081	0.7858	1B	0.798	0.814	0.8286	0.8392	0.0106	0.8750
		2A	0.0016	0.8734	0.8631		0.8270	0.8216	0.0054	0.7858	2B	0.798	0.814	0.8286	0.8356	0.0070	0.8750
		3A	0.0000	0.8750	0.8647		0.8286	0.8245	0.0041	0.7874	3B	0.7980	0.8068	0.8286	0.8339	0.0053	0.8750
⅞–16	UN	2A	0.0015	0.8735	0.8641		0.8329	0.8280	0.0049	0.7968	2B	0.807	0.821	0.8344	0.8407	0.0063	0.8750
		3A	0.0000	0.8750	0.8656		0.8344	0.8308	0.0036	0.7983	3B	0.8070	0.8158	0.8344	0.8391	0.0047	0.8750
⅞–20	UNEF	2A	0.0013	0.8737	0.8656		0.8412	0.8368	0.0044	0.8124	2B	0.821	0.832	0.8425	0.8482	0.0057	0.8750
		3A	0.0000	0.8750	0.8669		0.8425	0.8392	0.0033	0.8137	3B	0.8210	0.8287	0.8425	0.8468	0.0043	0.8750
15/16–12	UN	2A	0.0017	0.9358	0.9244		0.8817	0.8760	0.0057	0.8336	2B	0.847	0.865	0.8834	0.8908	0.0074	0.9375
		3A	0.0000	0.9375	0.9261		0.8834	0.8793	0.0011	0.8353	3B	0.8470	0.8575	0.8834	0.8889	0.0055	0.9375
15/16–16	UN	2A	0.0015	0.9360	0.9266		0.8954	0.8904	0.0050	0.8593	2B	0.870	0.884	0.8969	0.9034	0.0065	0.9375
		3A	0.0000	0.9375	0.9281		0.8969	0.8932	0.0037	0.8608	3B	0.8700	0.8783	0.8969	0.9013	0.0049	0.9375

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15/16–20	UNEF	2A	0.0014	0.9361	0.9280		0.9036	0.8991	0.0045	0.8748	2B	0.883	0.895	0.9050	0.9109	0.0059	0.9375
		3A	0.0000	0.9375	0.9294		0.9050	0.9016	0.0034	0.8762	3B	0.8830	0.9050	0.9094	0.0044	0.9375
		1A	0.0020	0.9980	0.9755		0.9168	0.9067	0.0101	0.8446	1B	0.865	0.890	0.9188	0.9320	0.0132	1.0000
1–8	UNC	2A	0.0020	0.9980	0.9830	0.9755	0.9168	0.9100	0.0068	0.8446	2B	0.865	0.890	0.9188	0.9276	0.0088	1.0000
		3A	0.0000	1.0000	0.9850		0.9188	0.9137	0.0051	0.8466	3B	0.8650	0.8797	0.9188	0.9254	0.0066	1.0000
		1A	0.0018	0.9982	0.9810		0.9441	0.9353	0.0088	0.8960	1B	0.910	0.928	0.9459	0.9573	0.0114	1.0000
1–12	UNF	2A	0.0018	0.9982	0.9868		0.9441	0.9382	0.0059	0.8960	2B	0.910	0.928	0.9459	0.9535	0.0076	1.0000
		3A	0.0000	1.0000	0.9886		0.9459	0.9415	0.0044	0.8978	3B	0.9100	0.9198	0.9459	0.9516	0.0057	1.0000
		2A	0.0015	0.9985	0.9891		0.9579	0.9529	0.0050	0.9218	2B	0.932	0.946	0.9594	0.9659	0.0065	1.0000
1–16	UN	3A	0.0000	1.0000	0.9906		0.9594	0.9557	0.0037	0.9233	3B	0.9320	0.9408	0.9594	0.9643	0.0049	1.0000
		2A	0.0014	0.9986	0.9905		0.9661	0.9616	0.0045	0.9373	2B	0.946	0.957	0.9675	0.9734	0.0059	1.0000
1–20	UNEF	3A	0.0000	1.0000	0.9919		0.9675	0.9641	0.0034	0.9387	3B	0.9460	0.9537	0.9675	0.9719	0.0044	1.0000
		2A	0.0017	1.0608	1.0494		1.0067	1.0010	0.0057	0.9586	2B	0.972	0.990	1.0084	1.0158	0.0074	1.0625
1 1/16–12	UN	3A	0.0000	1.0625	1.0511		1.0084	1.0042	0.0042	0.9603	3B	0.9720	0.9823	1.0084	1.0139	0.0055	1.0625
		2A	0.0015	1.0610	1.0516		1.0204	1.0154	0.0050	0.9843	2B	0.995	1.009	1.0219	1.0284	0.0065	1.0625
1 1/16–16	UN	3A	0.0000	1.0625	1.0531		1.0219	1.0182	0.0037	0.9853	3B	0.9950	1.0033	1.0219	1.0268	0.0049	1.0625
		2A	0.0014	1.0611	1.0524		1.0250	1.0203	0.0047	0.9929	2B	1.002	1.015	1.0264	1.0326	0.0062	1.0625
1 1/16–18	NEF	3A	0.0000	1.0625	1.0538		1.0264	1.0228	0.0036	0.9943	3B	1.0020	1.0105	1.0264	1.0310	0.0046	1.0625
		1A	0.0022	1.1228	1.0982		1.0300	1.0191	0.0109	0.9475	1B	0.970	0.998	1.0322	1.0463	0.0141	1.1250
1 1/16–7	UNC	2A	0.0022	1.1228	1.1064	1.0982	1.0300	1.0228	0.0072	0.9475	2B	0.970	0.998	1.0322	1.0416	0.0094	1.1250
		3A	0.0000	1.1250	1.1086		1.0322	1.0268	0.0054	0.9497	3B	0.9700	0.9875	1.0322	1.0393	0.0071	1.1250
		2A	0.0021	1.1229	1.1079		1.0417	1.0348	0.0069	0.9695	2B	0.900	1.015	1.0438	1.0528	0.0090	1.1250
1 1/16–8	N	3A	0.0000	1.1250	1.1100	1.1004	1.0438	1.0386	0.0052	0.9716	3B	0.9900	1.0047	1.0438	1.0505	0.0067	1.1250
		1A	0.0018	1.1232	1.1060		1.0691	1.0601	0.0090	1.0210	1B	1.035	1.053	1.0709	1.0826	0.0117	1.1250
1 1/16–12	UNF	2A	0.0018	1.1232	1.1118		1.0691	1.0631	0.0060	1.0210	2B	1.035	1.053	1.0709	1.0787	0.0078	1.1250
		3A	0.0000	1.1250	1.1136		1.0709	1.0664	0.0045	1.0228	3B	1.0350	1.0448	1.0709	1.0768	0.0059	1.1250
1 1/16 to 1 1/4–12																		
1 1/16–16	UN	2A	0.0015	1.1235	1.1141		1.0829	1.0779	0.0050	1.0468	2B	1.057	1.071	1.0844	1.0909	0.0065	1.1250
		3A	0.0000	1.1250	1.1156		1.0844	1.0807	0.0037	1.0483	3B	1.0570	1.0658	1.0844	1.0893	0.0049	1.1250
1 1/16–18	NEF	2A	0.0014	1.1236	1.1149		1.0875	1.0828	0.0047	1.0554	2B	1.065	1.078	1.0889	1.0951	0.0062	1.1250
		3A	0.0000	1.1250	1.1163		1.0889	1.0853	0.0036	1.0568	3B	1.0650	1.0730	1.0889	1.0935	0.0046	1.1250
1 1/16–12	UN	2A	0.0017	1.1858	1.1744		1.1317	1.1259	0.0058	1.0836	2B	1.097	1.115	1.1334	1.1409	0.0075	1.1875
		3A	0.0000	1.1875	1.1761		1.1334	1.1291	0.0043	1.0853	3B	1.0970	1.1073	1.1334	1.1390	0.0056	1.1875
1 3/16	UN	2A	0.0015	1.1860	1.1766		1.1454	1.1403	0.0051	1.1093	2B	1.120	1.134	1.1469	1.1535	0.0066	1.1875
		3A	0.0000	1.1875	1.1781		1.1469	1.1431	0.0038	1.1108	3B	1.1200	1.1283	1.1469	1.1519	0.0050	1.1875
1 3/16–18	NEF	2A	0.0015	1.1860	1.1773		1.1499	1.1450	0.0049	1.1178	2B	1.127	1.140	1.1514	1.1577	0.0063	1.1875
		3A	0.0000	1.1875	1.1788		1.1514	1.1478	0.0036	1.1193	3B	1.1270	1.1355	1.1514	1.1561	0.0047	1.1875

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TABLE 14.1 Standard Limits of Size: Unified and American Screw Threads (*Continued*)

Nominal size and threads per inch	Series designation	External									Internal						
				Major diameter limits, in			Pitch diameter limits, in			Minor diameter, in		Minor diameter limits, in		Pitch diameter limits, in			Major diameter, in
		Class	Allowance, in	Max*	Min	Min†	Max*	Min	Tolerance		Class	Min	Max	Min	Max	Tolerance	Min
1⅛–16 to 1¾–12																	
1¼–7	UNC	1A	0.0022	1.2478	1.2232		1.1550	1.1439	0.0111	1.0725	1B	1.095	1.123	1.1572	1.1716	0.0144	1.2500
		2A	0.0022	1.2478	1.2314	1.2232	1.1550	1.1476	0.0074	1.0725	2B	1.095	1.123	1.1572	1.1668	0.0096	1.2500
		3A	0.0000	1.2500	1.2336		1.1572	1.1517	0.0055	1.0747	3B	1.0950	1.1125	1.1572	1.1644	0.0072	1.2500
1¼–8	N	2A	0.0021	1.2479	1.2329	1.2254	1.1667	1.597	0.0070	1.0945	2B	1.115	1.140	1.1688	1.1780	0.0092	1.2500
		3A	0.0000	1.2500	1.2350		1.1688	1.1635	0.0053	1.0966	3B	1.1150	1.1297	1.1688	1.1757	0.0069	1.2500
1¼–12	UNF	1A	0.0018	1.2482	1.2310		1.1941	1.1849	0.0092	1.1460	1B	1.160	1.178	1.1959	1.2079	0.0120	1.2500
		2A	0.0018	1.2482	1.2368		1.1941	1.1879	0.0062	1.1460	2B	1.160	1.178	1.1959	1.2039	0.0080	1.2500
		3A	0.0000	1.2500	1.2386		1.1959	1.1913	0.0046	1.1478	3B	1.1600	1.1698	1.1959	1.2019	0.0060	1.2500
1¼–16	UN	2A	0.0015	1.2485	1.2391		1.2079	1.2028	0.0051	1.1718	2B	1.182	1.196	1.2094	1.2160	0.0066	1.2500
		3A	0.0000	1.2500	1.2406		1.2094	1.2056	0.0038	1.1733	3B	1.1820	1.1908	1.2094	1.2144	0.0050	1.2500
1¼–18	NEF	2A	0.0015	1.2485	1.2398		1.2124	1.2075	0.0049	1.1803	2B	1.190	1.203	1.2139	1.2202	0.0063	1.2500
		3A	0.0000	1.2500	1.2413		1.2139	1.2103	0.0036	1.1818	3B	1.1900	1.1980	1.2139	1.2186	0.0047	1.2500
1⅝–12	UN	2A	0.0017	1.3108	1.2994		1.2567	1.2509	0.0058	1.2086	2B	1.222	1.240	1.2584	1.2659	0.0075	1.3125
		3A	0.0000	1.3125	1.3011		1.2584	1.2541	0.0043	1.2103	3B	1.2220	1.2323	1.2584	1.2640	0.0056	1.3125
1⅝–16	UN	2A	0.0015	1.3110	1.3016		1.2704	1.2653	0.0051	1.2343	2B	1.245	1.259	1.2719	1.2785	0.0066	1.3125
		5A	0.0000	1.3125	1.3031		1.2719	1.2681	0.0038	1.2358	3B	1.2450	1.2533	1.2719	1.2769	0.0050	1.3125
1⅝–18	NEF	2A	0.0015	1.3110	1.3023		1.2749	1.2700	0.0049	1.2428	2B	1.252	1.265	1.2764	1.2827	0.0063	1.3125
		3A	0.0000	1.3125	1.3038		1.2764	1.2728	0.0036	1.2443	3B	1.2520	1.2605	1.2764	1.2811	0.0047	1.3125
1⅜–6	UNC	1A	0.0024	1.3726	1.3453		1.2643	1.2523	0.0120	1.1681	1B	1.195	1.225	1.2667	‡1.2822	§0.0155	1.3750
		2A	0.0024	1.3726	1.3544	1.3453	1.2643	1.2563	0.0080	1.1681	2B	1.195	1.225	1.2667	1.2771	0.0104	1.3750
		3A	0.0900	1.3750	1.3568		1.2667	1.2607	0.0060	1.1705	3B	1.1950	1.2146	1.2667	1.2745	0.0078	1.3750
1⅜–8	N	2A	0.0022	1.3728	1.3578	1.3503	1.2916	1.2844	0.0072	1.2194	2B	1.240	1.265	1.2938	1.3031	0.0093	1.3750
		3A	0.0000	1.3750	1.3600		1.2938	1.2884	0.0054	1.2216	3B	1.2400	1.2547	1.2938	1.3008	0.0070	1.3750

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1⅜–12	UNF	1A	0.0019	1.3731	1.3559		1.3190	1.3096	0.0094	1.2709	1B	1.285	1.303	1.3209	1.3332	0.0123	1.3750
		2A	0.0019	1.3731	1.3617		1.3190	1.3127	0.0063	1.2709	2B	1.285	1.303	1.3209	1.3291	0.0082	1.3750
		3A	0.0000	1.3750	1.3636		1.3209	1.3162	0.0047	1.2728	3B	1.2850	1.2948	1.3209	1.3270	0.0061	1.3750
1⅜–16	UN	2A	0.0015	1.3735	1.3641		1.3329	1.3278	0.0051	1.2968	2B	1.307	1.321	1.3344	1.3410	0.0066	1.3750
		3A	0.0000	1.3750	1.3656		1.3344	1.3306	0.0038	1.2983	3B	1.3070	1.3158	1.3344	1.3394	0.0050	1.3750
1⅜–18	NEF	2A	0.0015	1.3735	1.3648		1.3374	1.3325	0.0049	1.3053	2B	1.315	1.328	1.3389	1.3452	0.0063	1.3750
		3A	0.0000	1.3750	1.3663		1.3389	1.3353	0.0036	1.3068	3B	1.3150	1.3230	1.3389	1.3436	0.0047	1.3750
1⅞–12	UN	2A	0.0018	1.4357	1.4243		1.3816	1.3757	0.0059	1.3335	2B	1.347	1.365	1.3834	1.3910	0.0076	1.4375
		3A	0.0000	1.4375	1.4261		1.3834	1.3790	0.0044	1.3353	3B	1.3470	1.3573	1.3834	1.3891	.0057	1.4375
1⅞–16	UN	2A	0.0016	1.4359	1.4265		1.3953	1.3901	0.0052	1.3592	2B	1.370	1.384	1.3969	1.4037	0.0068	1.4375
		3A	0.0000	1.4375	1.4281		1.3969	1.3930	0.0039	1.3608	3B	1.3700	1.3783	1.3969	1.4020	0.0051	1.4375
1⅞–18	NEF	2A	0.0015	1.4360	1.4273		1.3999	1.3949	0.0050	1.3678	2B	1.377	1.390	1.4014	1.4079	0.0065	1.4375
		3A	0.0000	1.4375	1.4288		1.4014	1.3977	0.0037	1.3693	3B	1.3770	1.3855	1.4014	1.4062	0.0048	1.4375
		1A	0.0024	1.4976	1.4703		1.3893	1.3772	0.0121	1.2931	1B	1.320	1.350	1.3917	1.4075	0.0158	1.5000
1½–6	UNC	2A	0.0024	1.4976	1.4794	1.4703	1.3893	1.3812	0.0081	1.2931	2B	1.320	1.350	1.3917	1.4022	0.0105	1.5000
		3A	0.0000	1.5000	1.4818		1.3917	1.3856	0.0061	1.2955	3B	1.3200	1.3396	1.3917	1.3996	0.0079	1.5000
		2A	0.0022	1.4978	1.4828		1.4166	1.4093	0.0073	1.3444	2B	1.365	1.390	1.4188	1.4283	0.0095	1.5000
1½–8	N	3A	0.0000	1.5000	1.4850	1.4753	1.4188	1.4133	0.0055	1.3466	3B	1.3650	1.3797	1.4188	1.4259	0.0071	1.5000
		1A	0.0019	1.4981	1.4809		1.4440	1.4344	0.0096	1.3959	1B	1.410	1.428	1.4459	1.4584	0.0125	1.5000
1½–12	UNF	2A	0.0019	1.4981	1.4867		1.4440	1.4376	0.0064	1.3959	2B	1.410	1.428	1.4459	1.4542	0.0083	1.5000
		3A	0.0000	1.5000	1.4886		1.4459	1.4411	0.0048	1.3978	3B	1.4100	1.4198	1.4459	1.4522	0.0063	1.5000
1½–16	UN	2A	0.0016	1.4984	1.4890		1.4578	1.4526	0.0052	1.4217	2B	1.432	1.446	1.4594	1.4662	0.0068	1.5000
		3A	0.0000	1.5000	1.4906		1.4594	1.4555	0.0039	1.4233	3B	1.4320	1.4408	1.4594	1.4645	0.0051	1.5000
1½–18	NEF	2A	0.0015	1.4985	1.4898		1.4624	1.4574	0.0050	1.4303	2B	1.440	1.452	1.4639	1.4704	0.0065	1.5000
		3A	0.0000	1.5000	1.4913		1.4639	1.4602	0.0037	1.4318	3B	1.4400	1.4480	1.4639	1.4687	0.0048	1.5000
1⅝–16	N	2A	0.0016	1.5609	1.5515		1.5203	1.5151	0.0052	1.4842	2B	1.495	1.509	1.5219	1.5287	0.0068	1.5625
		3A	0.0000	1.5625	1.5531		1.5219	1.5180	0.0039	1.4858	3B	1.4950	1.5033	1.5219	1.5270	0.0051	1.5625
1⅝–18	NEF	2A	0.0015	1.5610	1.5523		1.5249	1.5199	0.0050	1.4928	2B	1.502	1.515	1.5264	1.5329	0.0065	1.5625
		3A	0.0000	1.5625	1.5538		1.5264	1.5227	0.0037	1.4943	3B	1.5020	1.5105	1.5264	1.5312	0.0048	1.5625

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TABLE 14.1 Standard Limits of Size: Unified and American Screw Threads (*Continued*)

Nominal size and threads per inch	Series designation	External									Internal						
				Major diameter limits, in			Pitch diameter limits, in			Minor diameter, in		Minor diameter limits, in		Pitch diameter limits, in			Major diameter, in
		Class	Allowance, in	Max*	Min	Min†	Max*	Min	Tolerance		Class	Min	Max	Min	Max	Tolerance	Min
1⅛–16 to 1¾–12																	
1⅝–8	N	2A	0.0022	1.6228	1.6078	1.6003	1.5416	1.5342	0.0074	1.4694	2B	1.490	1.515	1.5438	1.5535	0.0097	1.6250
		3A	0.0000	1.6250	1.6100		1.5438	1.5382	0.0056	1.4716	3B	1.4900	1.5047	1.5438	1.5510	0.0072	1.6250
1⅝–12	UN	2A	0.0018	1.6232	1.6118		1.5691	1.5632	0.0059	1.5210	2B	1.535	1.553	1.5709	1.5785	0.0076	1.6250
		3A	0.0000	1.6250	1.6136		1.5709	1.5665	0.0044	1.5228	3B	1.5350	1.5448	1.5709	1.5766	0.0057	1.6250
1⅝–16	UN	2A	0.0016	1.6234	1.6140		1.5828	1.5776	0.0052	1.5467	2B	1.557	1.571	1.5844	1.5912	0.0068	1.6250
		3A	0.0000	1.6250	1.6156		1.5814	1.5805	0.0039	1.5483	3B	1.5570	1.5658	1.5844	1.5895	0.0051	1.6250
1⅝–18	NEF	2A	0.0015	1.6235	1.6148		1.5874	1.5824	0.0050	1.5553	2B	1.565	1.578	1.5889	1.5954	0.0065	1.6250
		3A	0.0000	1.6250	1.6163		1.5889	1.5852	0.0037	1.5568	3B	1.5650	1.5730	1.5889	1.5937	0.0048	1.6250
1 1/16–16	N	2A	0.0016	1.6859	1.6765		1.6453	1.6400	0.0053	1.6092	2B	1.620	1.634	1.6469	1.6538	0.0069	1.6875
		3A	0.0000	1.6875	1.6781		1.6469	1.6429	0.0040	1.6108	3B	1.6200	1.6283	1.6469	1.6521	0.0052	1.6875
1 1/16–18	NEF	2A	0.0015	1.6860	1.6773		1.6499	1.6448	0.0051	1.6178	2B	1.627	1.640	1.6514	1.6580	0.0066	1.6875
		3A	0.0000	1.6875	1.6788		1.6514	1.6476	0.0038	1.6193	3B	1.6270	1.6355	1.6514	1.6563	0.0049	1.6875
1¾–5	UNC	1A	0.0027	1.7473	1.7165		1.6174	1.6040	0.0134	1.5019	1B	1.534	1.568	1.6201	1.6375	0.0174	1.7500
		2A	0.0027	1.7473	1.7268	1.7165	1.6174	1.6085	0.0089	1.5019	2B	1.534	1.568	1.6201	1.6317	0.0116	1.7500
		3A	0.0000	1.7500	1.7295		1.6201	1.6134	0.0067	1.5046	3B	1.5340	1.5575	1.6201	1.6288	0.0087	1.7500
1¾–8	N	2A	0.0023	1.7477	1.7327	1.7252	1.6665	1.6590	0.0075	1.5943	2B	1.615	1.640	1.6688	1.6786	0.0098	1.7500
		3A	0.0000	1.7300	1.7350		1.6688	1.6632	0.0056	1.5966	3B	1.6150	1.6297	1.6688	1.6762	0.0074	1.7500
1¾–12	UN	2A	0.0018	1.7482	1.7368		1.6941	1.6881	0.0060	1.6460	2B	1.660	1.678	1.6959	1.7037	0.0078	1.7500
		3A	0.0000	1.7500	1.7386		1.6959	1.6914	0.0045	1.6478	3B	1.6600	1.6698	1.6959	1.7017	0.0058	1.7500
1¾–16 to 3–16																	
1¾–16	UNEF	2A	0.0016	1.7484	1.7390		1.7078	1.7025	0.0053	1.6717	2B	1.682	1.696	1.7094	1.7163	0.0069	1.7500
		3A	0.0000	1.7500	1.7406		1.7094	1.7054	0.0040	1.6733	3B	1.6820	1.6906	1.7094	1.7146	0.0052	1.7500
1 13/16–16	N	2A	0.0016	1.8109	1.8015		1.7703	1.7650	0.0053	1.7342	2B	1.745	1.759	1.7719	1.7788	0.0069	1.8125
		3A	0.0000	1.8125	1.8031		1.7719	1.7679	0.0040	1.7358	3B	1.7450	1.7533	1.7719	1.7771	0.0052	1.8125
1⅞–8	N	2A	0.0023	1.8727	1.8577	1.8502	1.7915	1.7838	0.0077	1.7193	2B	1.740	1.765	1.7938	1.8038	0.0100	1.8750
		3A	0.0000	1.8750	1.8600		1.7938	1.7881	0.0057	1.7216	3B	1.7400	1.7547	1.7938	1.8013	0.0075	1.8750

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1⅞–12	UN	2A	0.0018	1.8732	1.8618		1.8191	1.8131	0.0060	1.7710	2B	1.785	1.803	1.8209	1.8287	0.0078	1.8750
		3A	0.0000	1.8750	1.8636		1.8209	1.8164	0.0045	1.7728	3B	1.7850	1.7948	1.8209	1.8267	0.0058	1.8750
1⅞–16	UN	2A	0.0016	1.8734	1.8640		1.8328	1.8275	0.0053	1.7967	2B	1.807	1.821	1.8344	1.8413	0.0069	1.8750
		3A	0.0000	1.8750	1.8656		1.8344	1.8304	0.0040	1.7983	3B	1.8070	1.8158	1.8344	1.8396	0.0052	1.8750
1 15/16–16	N	2A	0.0016	1.9359	1.9265		1.8953	1.8899	0.0054	1.8592	2B	1.870	1.884	1.8969	1.9039	0.0070	1.9375
		3A	0.0000	1.9375	1.9281		1.8969	1.8929	0.0040	1.8608	3B	1.8700	1.8783	1.8969	1.9021	.0052	1.9375
		1A	0.0029	1.9971	1.9641		1.8528	1.8385	0.0143	1.7245	1B	1.759	1.795	1.8557	1.8743	0.0186	2.0000
2–4½	UNC	2A	0.0029	1.9971	1.9751	1.9641	1.8528	1.8433	0.0095	1.7245	2B	1.759	1.795	1.8557	1.8681	0.0124	2.0000
		3A	0.0000	2.0000	1.9780		1.8557	1.8486	0.0071	1.7274	3B	1.7590	1.7861	1.8557	1.8650	0.0093	2.0000
2–8	N	2A	0.0023	1.9977	1.9827		1.9165	1.9087	0.0078	1.8443	2B	1.865	1.890	1.9188	1.9289	0.0101	2.0000
		3A	0.0000	2.0000	1.9850	1.9752	1.9188	1.9130	0.0058	1.8466	3B	1.8650	1.8797	1.9188	1.9264	0.0076	2.0000
2–12	UN	2A	0.0018	1.9982	1.9868		1.9441	1.9380	0.0061	1.8960	2B	1.910	1.928	1.9459	1.9538	0.0079	2.0000
		3A	0.0000	2.0000	1.9886		1.9459	1.9414	0.0045	1.8978	3B	1.9100	1.9198	1.9459	1.9518	0.0059	2.0000
2–16	UNEF	2A	0.0016	1.9984	1.9890		1.9578	1.9524	0.0054	1.9217	2B	1.932	1.946	1.9594	1.0664	0.0070	2.0000
		3A	0.0000	2.0000	1.9906		1.9594	1.9554	0.0040	1.9233	3B	1.9320	1.9408	1.9594	1.9646	0.0052	2.0000
2 1/16–16	N	2A	0.0016	2.0609	2.0515		2.0203	2.0149	0.0054	1.9842	2B	1.995	2.009	2.0219	2.0289	0.0070	2.0625
		3A	0.0000	2.0625	2.0531		2.0219	2.0179	0.0040	1.9858	3B	1.9950	2.0033	2.0219	2.0271	0.0052	2.0625
2⅛–8	N	2A	0.0024	2.1226	2.1076		2.0414	2.0335	0.0079	1.9692	2B	1.990	2.015	2.0438	2.0540	0.0102	2.1250
		3A	0.0000	2.1250	2.1100	2.1001	2.0438	2.0379	0.0059	1.9716	3B	1.9900	2.0047	2.0438	2.0515	0.0077	2.1250
2⅛–12	UN	2A	0.0018	2.1232	2.1118		2.0691	2.0630	0.0061	2.0210	2B	2.035	2.053	2.0709	2.0788	0.0079	2.1250
		3A	0.0000	2.1250	2.1136		2.0709	2.0664	0.0045	2.0228	3B	2.0350	2.0448	2.0709	2.0768	0.0059	2.1250
2⅛–16	UN	2A	0.0016	2.1234	2.1140		2.0828	2.0774	0.0054	2.0467	2B	2.057	2.071	2.0844	2.0914	0.0070	2.1250
		3A	0.0000	2.1250	2.1156		2.0844	2.0803	0.0041	2.0483	3B	2.0570	2.0658	2.0844	2.0896	0.0052	2.1250
2⅜–16	N	2A	0.0016	2.1859	2.1765		2.1453	2.1399	0.0054	2.1092	2B	2.120	2.134	2.1469	2.1539	0.0070	2.1875
		3A	0.0000	2.1875	2.1781		2.1469	2.1428	0.0041	2.1108	3B	2.1200	2.1283	2.1469	2.1521	0.0052	2.1875
2½–4½	UNC	1A	0.0029	2.2471	2.2141		2.1028	2.0882	0.0146	1.9745	1B	2.009	2.045	2.1057	2.1247	0.0190	2.2500
		2A	0.0029	2.2471	2.2251	2.2141	2.1028	2.0931	0.0097	1.9745	2B	2.009	2.045	2.1057	2.1183	0.0126	2.2500
		3A	0.0000	2.2500	2.2280		2.1057	2.0984	0.0073	1.9774	3B	2.0090	2.0361	2.1057	2.1152	0.0095	2.2500
2½–8	N	2A	0.0024	2.2476	2.2326		2.1664	2.1584	0.0080	2.0942	2B	2.115	2.140	2.1688	2.1792	0.0104	2.2500
		3A	0.0000	2.2500	2.2350	2.2251	2.1688	2.1628	0.0060	2.0966	3B	2.1150	2.1297	2.1688	2.1766	0.0078	2.2500
		2A	0.0018	2.2482	2.2368		2.1941	2.1880	0.0061	2.1460	2B	2.160	2.178	2.1959	2.2038	0.0079	2.2500
2½–12	UN	3A	0.0000	2.2500	2.2386		2.1959	2.1914	0.0045	2.1478	3B	2.1600	2.1698	2.1959	2.2018	0.0059	2.2500

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TABLE 14.1 Standard Limits of Size: Unified and American Screw Threads (*Continued*)

Nominal size and threads per inch	Series designation	External									Internal						
				Major diameter limits, in			Pitch diameter limits, in			Minor diameter, in		Minor diameter limits, in		Pitch diameter limits, in			Major diameter, in
		Class	Allowance, in	Max*	Min	Min†	Max*	Min	Tolerance		Class	Min	Max	Min	Max	Tolerance	Min
1¾–16 to 3–16																	
2¼–16	UN	2A	0.0016	2.2484	2.2390		2.2078	2.2024	0.0054	2.1717	2B	2.182	2.196	2.2094	2.2164	0.0070	2.2500
		3A	0.0000	2.2500	2.2406		2.2094	2.2053	0.0041	2.1733	3B	2.1820	2.1908	2.2094	2.2146	0.0052	2.2500
2⅝–16	N	2A	0.0017	2.3108	2.3014		2.2702	2.2647	0.0055	2.2341	2B	2.245	2.259	2.2719	2.2791	0.0072	2.3125
		3A	0.0000	2.3125	2.3031		2.2719	2.2678	0.0041	2.2358	3B	2.2450	2.2533	2.2719	2.2773	0.0054	2.3125
2¾–12	UN	2A	0.0019	2.3731	2.3617		2.3190	2.3128	0.0062	2.2709	2B	2.285	2.303	2.3209	2.3290	0.0081	2.3750
		3A	0.0000	2.3750	2.3636		2.3209	2.3163	0.0046	2.2728	3B	2.2850	2.2948	2.3209	2.3269	0.0060	2.3750
2¾–16	UN	2A	0.0017	2.3733	2.3639		2.3327	2.3272	0.0055	2.2966	2B	2.307	2.321	2.3344	2.3416	0.0072	2.3750
		3A	0.0000	2.3750	2.3656		2.3344	2.3303	0.0041	2.2983	3B	2.3070	2.3158	2.3344	2.3398	0.0054	2.3750
2⅞–16	N	2A	0.0017	2.4358	2.4264		2.3953	2.3897	0.0055	2.3591	2B	2.370	2.384	2.3969	2.4041	0.0072	2.4375
		3A	0.0000	2.4375	2.4281		2.3969	2.3928	0.0041	2.3608	3B	2.3700	2.3783	2.3969	2.4023	0.0054	2.4375
2½–4	UNC	1A	0.0031	2.4969	2.4612		2.3345	2.3190	0.0155	2.1902	1B	2.229	2.267	2.3376	2.3578	0.0202	2.5000
		2A	0.0031	2.4969	2.4731	2.4612	2.3345	2.3241	0.0104	2.1902	2B	2.229	2.267	2.3376	2.3511	0.0135	2.5000
		3A	0.0000	2.5000	2.4762		2.3376	2.3298	0.0078	2.1933	3B	2.2290	2.2594	2.3376	2.3477	0.0101	2.5000
2½–8	N	2A	0.0024	2.4976	2.4826	2.4751	2.4164	2.4082	0.0082	2.3442	2B	2.365	2.390	2.4188	2.4294	0.0106	2.5000
		3A	0.0000	2.5000	2.4850		2.4188	2.4127	0.0061	2.3466	3B	2.3650	2.3797	2.4188	2.4268	0.0080	2.5000
2½–12	UN	2A	0.0019	2.4981	2.4867		2.4440	2.4378	0.0062	2.3959	2B	2.410	2.428	2.4459	2.4540	0.0081	2.5000
		3A	0.0000	2.5000	2.4886		2.4459	2.4413	0.0046	2.3978	3B	2.4100	2.4198	2.4459	2.4519	0.0060	2.5000
2½–16	UN	2A	0.0017	2.4983	2.4889		2.4577	2.4522	0.0055	2.4216	2B	2.432	2.446	2.4594	2.4666	0.0072	2.5000
		3A	0.0000	2.5000	2.4906		2.4594	2.4553	0.0041	2.4233	3B	2.4320	2.4408	2.4594	2.4648	0.0054	2.5000
2⅝–12	UN	2A	0.0019	2.6231	2.6117		2.5690	2.5628	0.0062	2.5209	2B	2.535	2.553	2.5709	2.5790	0.0081	2.6250
		3A	0.0000	2.6250	2.6136		2.5709	2.5663	0.0046	2.5228	3B	2.5350	2.5448	2.5709	2.5769	0.0060	2.6250
2⅝–16	UN	2A	0.0017	2.6233	2.6139		2.5827	2.5772	0.0055	2.5466	2B	2.557	2.571	2.5844	2.5916	0.0072	2.6250
		3A	0.0000	2.6250	2.6156		2.5844	2.5803	0.0041	2.5483	3B	2.5570	2.5658	2.5844	2.5898	0.0054	2.6250
2¾–4	UNC	1A	0.0032	2.7468	2.7111		2.5844	2.5686	0.0158	2.4401	1B	2.479	2.517	2.5876	2.6082	0.0206	2.7500
		2A	0.0032	2.7468	2.7230	2.7111	2.5844	2.5739	0.0105	2.4401	2B	2.479	2.517	2.5876	2.6013	0.0137	2.7500
		3A	0.0000	2.7500	2.7262		2.5876	2.5797	0.0079	2.4433	3B	2.4790	2.5094	2.5876	2.5979	0.0103	2.7500

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$2\frac{3}{4}$–8	N	2A	0.0025	2.7475	2.7325	2.7250	2.6663	2.0580	0.0083	2.5941	2B	2.615	2.640	2.6688	2.6796	0.0108	2.7500
		3A	0.0000	2.7500	2.7350		2.6688	[‡]2.6625	[‡]0.0063	2.5966	3B	2.6150	2.6297	2.6688	2.6769	0.0081	2.7500
$2\frac{3}{4}$–12	UN	2A	0.0019	2.7481	2.7367		2.6940	2.6878	0.0062	2.6459	2B	2.660	2.678	2.6959	2.7040	0.0081	2.7500
		3A	0.0000	2.7500	2.7386		2.6959	2.6913	0.0046	2.6478	3B	2.6600	2.6698	2.6959	2.7019	0.0060	2.7500
$2\frac{3}{4}$–16	UN	2A	0.0017	2.7483	2.7389		2.7077	2.7022	0.0055	2.6716	2B	2.682	2.696	2.7094	2.7166	0.0072	2.7500
		3A	0.0000	2.7500	2.7406		2.7094	2.7053	0.0041	2.6733	3B	2.6820	2.6908	2.7094	2.7148	0.0054	2.7500
$2\frac{7}{8}$–12	UN	2A	0.0019	2.8731	2.8617		2.8190	2.8127	0.0063	2.7709	2B	2.785	2.803	2.8209	2.8291	0.0082	2.8750
		3A	0.0000	2.8750	2.8636		2.8209	2.8162	0.0047	2.7728	3B	2.7850	2.7948	2.8209	2.8271	0.0062	2.8750
$2\frac{7}{8}$–16	UN	2A	0.0017	2.8733	2.8639		2.8327	2.8271	0.0056	2.7966	2B	2.807	2.821	2.8344	2.8417	0.0073	2.8750
		3A	0.0000	2.8750	2.8656		2.8344	2.8302	0.0042	2.7983	3B	2.8070	2.8158	2.8344	2.8399	0.0055	2.8750
3–4	UNC	1A	0.0032	2.9968	2.9611	2.9611	2.8344	2.8183	0.0161	2.6901	1B	2.729	2.767	2.8376	2.8585	0.0209	3.0000
		2A	0.0032	2.9968	2.9730		2.8344	2.8237	0.0107	2.6901	2B	2.729	2.767	2.8376	2.8515	0.0139	3.0000
		3A	0.0000	3.0000	2.9762		2.8376	2.8296	0.0080	2.6933	3B	2.7290	2.7594	2.8376	2.8480	0.0104	3.0000
3–8	N	2A	0.0026	2.9974	2.9824	2.9749	2.9162	2.9077	0.0085	2.8440	2B	2.865	2.890	2.9188	2.9299	0.0111	3.0000
		3A	0.0000	3.0000	2.9850		2.9188	2.9124	0.0064	2.8466	3B	2.8650	2.8797	2.9188	2.9271	0.0083	3.0000
3–12	UN	2A	0.0019	2.9981	2.9867		2.9440	2.9377	0.0063	2.8959	2B	2.910	2.928	2.9459	2.9541	0.0082	3.0000
		3A	0.0000	3.0000	2.9886		2.9459	2.9412	0.0047	2.5978	3B	2.9100	2.9198	2.9459	2.9521	0.0062	3.0000
3–16	UN	2A	0.0017	2.9983	2.9889		2.9577	2.9521	0.0056	2.9216	2B	2.932	2.946	2.9594	2.9667	0.0073	3.0000
		3A	0.0000	3.0000	2.9906		2.9594	2.9552	0.0042	2.9233	3B	2.9320	2.9408	2.9594	2.9649	0.0055	3.0000

* For class 2A threads having an additive finish, the maximum is increased to the basic size, the value being the same as for class 3A shown in this column.

† For unfinished hot-rolled material.

SOURCE: Extracted from National Bureau of Standards Handbook H28 (1967), Part I (Screw-Thread Standards for Federal Services), which is in general agreement with *American Standard Unified Screw Threads* (ASA B1.1-1960).

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Thread engagement to prevent stripping. The calculation approach depends on the materials selected.

1. *Same materials* chosen for both external threaded part and internal threaded part:

$$E_L = \frac{2A_{ts}}{\pi D_m\{\frac{1}{2} + [n(p_d - D_m)/\sqrt{3}]\}}$$

where E_L = length of engagement of the thread, in
D_m = maximum minor diameter of internal thread, in
n = number of threads per in
A_{ts} = tensile stress area of screw thread as given in previous equation
P_d = minimum pitch diameter of external thread, in

2. *Different materials,* i.e., internal threaded part of lower strength than external threaded part: Determine relative strength of external thread and internal thread from

$$R = \frac{A_{se}(S_e)}{A_{si}(S_i)}$$

where R = relative strength factor
A_{se} = shear area of external thread, in^2
A_{si} = shear area of internal thread, in^2
S_e = tensile strength of external thread material, psi
S_i = tensile strength of internal thread material, psi

If $R \leq 1$, the length of engagement as determined by the equation in item 1 (above) is adequate to prevent stripping of the internal thread. If $R > 1$, the length of engagement G to prevent internal thread strip is

$$G = E_L R$$

In the immediately preceding equation, A_{se} and A_{si} are the shear areas and are calculated as follows:

$$A_{se} = \pi n E_L D_m \left(\frac{1}{2n} + \frac{p_d - D_m}{\sqrt{3}}\right)$$

$$A_{si} = \pi n E_L D_m \left(\frac{1}{2n} + \frac{D_M - D_p}{\sqrt{3}}\right)$$

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where D_p = maximum pitch diameter of internal thread, in
D_M = minimum major diameter of external thread, in

Other symbols have been defined previously.

14.2.2 Calculating the pitch diameter of unified and metric threads

It is often necessary to find the pitch diameter of various unified (UN) and metric (M) thread sizes. This would be necessary for threads that are not listed in the preceding tables of thread sizes and where the thread is larger than that normally listed in handbooks. These would include threads on large bolts and threads on jack screws and lead screws used on various machinery or machine tools. To calculate the pitch diameters, refer to Fig. 14.15.

$$H = 0.5\sqrt{3} \times p = 0.866025p$$

where p is the pitch of the thread. In the unified system this is equal to the reciprocal of the number of threads per in (i.e., for a ⅜-16 thread, the pitch would be 1/16 = 0.0625 in). For the metric system, the pitch is given in millimeters on the thread listing (i.e., on an M12 × 1.5 metric thread, the pitch would be 1.5 mm or 1.5 × 0.03937 in = 0.059055 in). In this equation, in addition, d is the basic diameter of the external thread (i.e., ⅜-16 would be 0.375 in; a no. 8-32 would be 0.164 in, etc.).

Example: Find the pitch diameter of a 0.375-16 UNC-3A thread using Fig. 14.15, where d is the basic outside diameter of the thread (= 0.375 in) and $H = 0.866025 \times p = 0.866025 \times 0.0625 = 0.054127$ in (for this case only).

We would next perform the following:

$$\text{Pitch diameter} = [d/2 - (5H/8) + (H/4)] \times 2$$

$$\text{Pitch diameter} = [0.375/2 - (5 \times 0.054127/8) + (0.054127/4)] \times 2$$

$$= 0.3344$$

If you check the basic pitch diameter for this thread in a table of pitch diameters, you will find that this is the correct answer when the thread is a class 3A and the pitch diameter is maximum. This may be verified by checking Table 14.1. Thus you may calculate any pitch diameter for the different classes of fits on any UN or M profile thread because the thread geometry is shown in Fig. 14.15. Pitch diameters for other classes or types of thread systems may be calculated when you know the basic thread geometry, as in this case for the UN and M thread systems.

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The various thread systems used worldwide are shown in Fig. 7.52 and include ISO-M and UN, UNJ (controlled root radii), Whitworth (BSW), American buttress (7° face), NPT (American National Pipe Thread), BSPT (British Standard Pipe Thread), Acme (29°), Acme (stub 29°), API (taper 1:6), TR DIN 103, and RD DIN 405 (round).

14.3 Rivets

Rivets form a large class of fastening devices and are manufactured in many types and varieties and various materials. Rivets are made from carbon steels, aluminum alloys, brass, copper, bronze, and other materials agreed on by the manufacturer and purchaser.

Head forms for standard rivets include button, truss, brazier, coopers, oval, and flush. Flush-head rivets are provided in the following countersunk head angles: 60°, 78°, 90°, 100°, 120°, 144°, and 150°. The most common countersunk forms are the 90° and 100° types. To employ these types of rivets, a countersinking tool is used to cut the recess for the flush head. When the material is thin, processes known as *dimpling* and *double-dimpling* are employed.

Figure 14.21 shows the dimpling methods, in which a dimpling tool is used to produce the countersunk recess for the rivet. This method is used on aerospace vehicles to attach the "skins," or outer metal layers, on the craft. Modern methods of adhesive bonding are being used extensively in conjunction with spot welding to manufacture large sections of aerospace vehicles in lieu of riveting. But riveting is still used for many fastening applications throughout industry and the construction trades.

Rivets are made for blind-hole applications in the form of pull-stem pop rivets, drive-stem rivets, and explosive rivets. Other forms include solid-stem, tubular, and semitubular rivets.

Rivet edge distance. The position or location of rivets from the edge of a part is normally $2d$, where d is the rivet shank diameter, with an absolute minimum of $1.5d$. The lateral spacing between rivets is known as *pitch* and is determined by the load requirements of the riveted joint. See Fig. 14.22 for an illustration of edge distance.

Rivet symbols on engineering drawings take the forms shown in Fig. 14.23. These symbols are encountered frequently on aerospace vehicle assembly drawings.

Other manufacturing techniques such as welding, spot welding, and structural adhesive bonding have replaced riveting in many applications. Nevertheless, riveting is still employed in a great number of industrial applications. The types and varieties of rivets are

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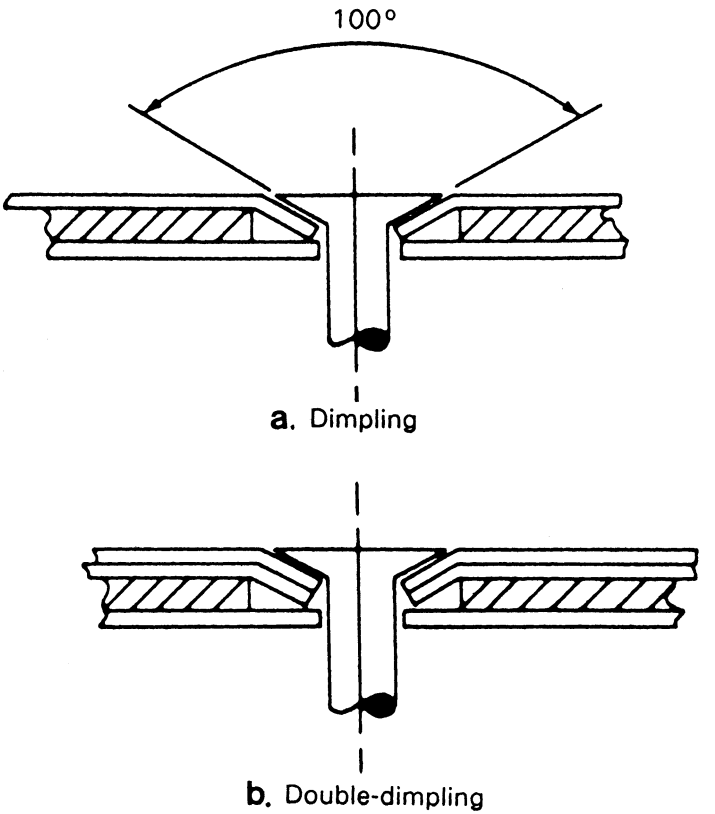

Figure 14.21 (*a*) Dimpling. (*b*) Double dimpling.

numerous, and a complete description and dimensional data, as well as materials specifications, are contained in the IFI handbooks on fasteners in both U.S. Customary and metric units.

14.3.1 General sizing of rivets

For rivet sizing (general, noncritical applications), the following approximations may be used:

$$d = 1.25\sqrt{t} \qquad \text{to} \qquad 1.45\sqrt{t}$$

where d is the diameter of the rivet shank in inches or millimeters (use next larger size), and t is the material thickness in inches.

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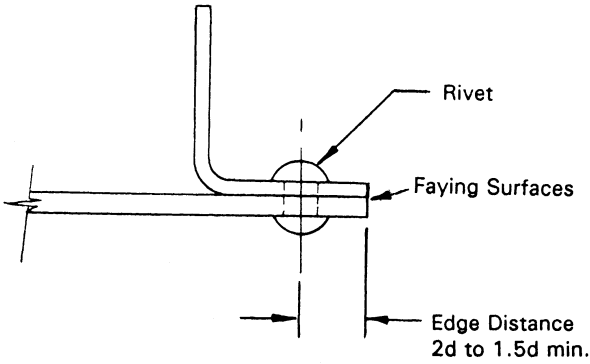

Figure 14.22 Rivet edge distance.

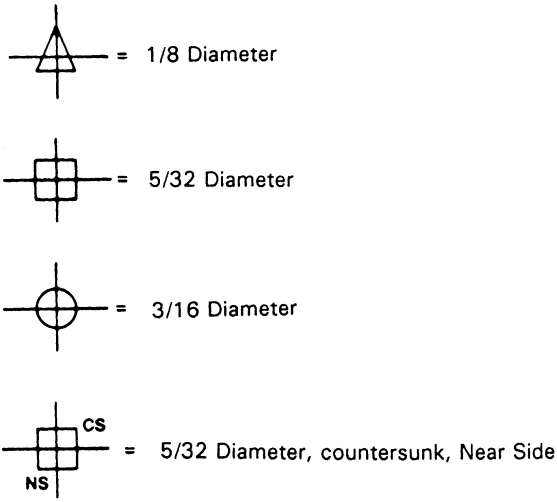

Figure 14.23 Standard rivet symbols.

14.4 Pins

Pins of various types are used throughout industry. Pins are available in different sizes, styles, and materials. This section details the most popular pins used in all types of design and assembly applications. The common-usage pins include

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- Clevis pins
- Cotter pins
- Spring pins (roll pins)
- Spiral spring pins
- Taper pins
- Dowel pins
- Grooved pins
- Quick-release pins

14.4.1 Clevis pins

Clevis pins are used where a quickly detachable pin is of benefit from a design and manufacturing standpoint. Figure 14.24 shows the sizes and dimensions of standard clevis pins. The clevis pin may be made of various materials, such as carbon steel, stainless steel, aluminum alloy, and other materials.

14.4.2 Cotter pins

Cotter pins are very common and economical fastening devices that see countless uses and applications throughout industry. The two most common types of cotter pins and their sizes and dimensions are shown in Fig. 14.25. The cotter pin is normally used with the standard clevis pin.

14.4.3 Spring pins (roll pins)

The slotted type of spring pin (sometimes called a *roll pin*) is used in applications where economy is important. This type of pin has been used to replace the tapered pin, dowel pin, and grooved pin in many applications because of its low cost and ease of preparation and assembly into holes with loose tolerances. Spring-temper carbon steel is usually used for these pins, but they are also available in other materials. Figure 14.26 shows the sizes, dimensions, and recommended hole diameters for spring-pin applications, along with the double-shear values for design reference. Placement of the slot in relation to shock loads for this type of pin can affect its performance and shock-absorbing qualities.

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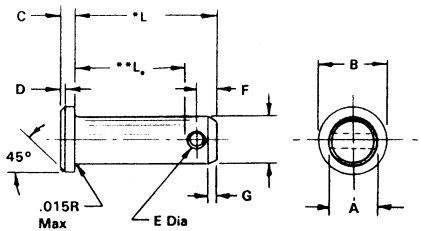

	A		B	C	D	E		F	G	
Basic Pin Diameter	Shank Diameter Max	Min	Head Diameter Max	Head Height Max	Head Chamfer ± 0.01	Hole Diameter Max	Min			Cotter Pin Size
0.188	0.186	0.181	0.32	0.07	0.02	0.088	0.073	0.09	0.055	1/16
0.250	0.248	0.243	0.38	0.10	0.03	0.088	0.073	0.09	0.055	1/16
0.312	0.311	0.306	0.44	0.10	0.03	0.119	0.104	0.12	0.071	3/32
0.375	0.373	0.368	0.51	0.13	0.03	0.119	0.104	0.12	0.071	3/32
0.438	0.436	0.431	0.57	0.16	0.04	0.119	0.104	0.12	0.071	3/32
0.500	0.496	0.491	0.63	0.16	0.04	0.151	0.136	0.15	0.089	1/8
0.625	0.621	0.616	0.82	0.21	0.06	0.151	0.136	0.15	0.089	1/8
0.750	0.746	0.741	0.94	0.26	0.07	0.182	0.167	0.18	0.110	5/32
0.875	0.871	0.866	1.04	0.32	0.09	0.182	0.167	0.18	0.110	5/32
1.000	0.996	0.991	1.19	0.35	0.10	0.182	0.167	0.18	0.110	5/32

*L = Total length under head
**L_e = Length of effective grip
Effective grip lengths must be selected from manufacturer's catalogs.

Figure 14.24 Standard clevis-pin dimensions.

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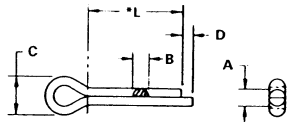
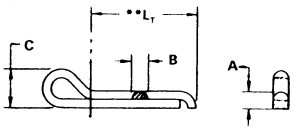


EXTENDED PRONG
SQUARE CUT TYPE

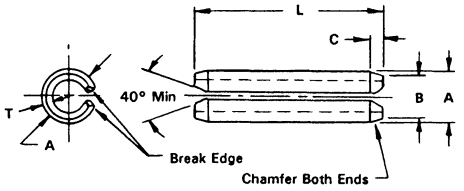


HAMMERLOCK TYPE

Basic Pin Diameter	Total Shank Diameter A	Wire Width Maximum B	Head Diameter Minimum C	Extended Prong Length, Minimum D	Recommended Hole Size
0.031	0.032	0.032	0.06	0.01	0.047
0.047	0.048	0.048	0.09	0.02	0.062
0.062	0.060	0.060	0.12	0.03	0.078
0.078	0.076	0.076	0.16	0.04	0.094
0.094	0.090	0.090	0.19	0.04	0.109
0.109	0.104	0.104	0.22	0.05	0.125
0.125	0.120	0.120	0.25	0.06	0.141
0.141	0.134	0.134	0.28	0.06	0.156
0.156	0.150	0.150	0.31	0.07	0.172
0.188	0.176	0.176	0.38	0.09	0.203
0.219	0.207	0.207	0.44	0.10	0.234
0.250	0.225	0.225	0.50	0.11	0.266
0.312	0.280	0.280	0.62	0.14	0.312
0.375	0.335	0.335	0.75	0.16	0.375
0.438	0.406	0.406	0.88	0.20	0.438
0.500	0.473	0.473	1.00	0.23	0.500
0.625	0.598	0.598	1.25	0.30	0.625
0.750	0.723	0.723	1.50	0.36	0.750

* L = Length
** L_T = Total length
Allow extra length for spreading and securing
Available lengths to be selected from manufacturer's catalogs.

Figure 14.25 Cotter-pin dimensions.



	A		B	C	T					
Basic Pin Diameter	Pin Diameter Max	Pin Diameter Min	Chamfer Dia.	Chamfer Lth.	Stock Thickness	Hole Diameter Recommended Max	Hole Diameter Recommended Min	Double Shear Load, Lb. ♦ AISI 1070 1095 & 420	AISI 302	Beryllium Copper
0.062	0.069	0.066	0.059	0.028	0.012	0.065	0.062	425	350	270
0.078	0.086	0.083	0.075	0.032	0.018	0.081	0.078	650	550	400
0.094	0.103	0.099	0.091	0.038	0.022	0.097	0.094	1,000	800	660
0.125	0.135	0.131	0.122	0.044	0.028	0.129	0.125	2,100	1,500	1,200
0.141	0.149	0.145	0.137	0.044	0.028	0.144	0.140	2,200	1,600	1,400
1.156	0.167	0.162	0.151	0.048	0.032	0.160	0.156	3,000	2,000	1,800
0.188	0.199	0.194	0.182	0.055	0.040	0.192	0.187	4,400	2,800	2,600
0.219	0.232	0.226	0.214	0.065	0.048	0.224	0.219	5,700	3,550	3,700
0.250	0.264	0.258	0.245	0.065	0.048	0.256	0.250	7,700	4,600	4,500
0.312	0.328	0.321	0.306	0.080	0.062	0.318	0.312	11,500	7,100	6,800
0.375	0.392	0.385	0.368	0.095	0.077	0.382	0.375	17,600	10,000	10,100
0.438	0.456	0.448	0.430	0.095	0.077	0.445	0.437	20,000	12,000	12,200
0.500	0.521	0.513	0.485	0.110	0.094	0.510	0.500	25,800	15,500	16,800
0.625	0.650	0.640	0.608	0.125	0.125	0.636	0.625	46,000	18,800	.....
0.750	0.780	0.769	0.730	0.150	0.150	0.764	0.750	66,000	23,200	.....

Length L, is selected from manufacturer's catalogs. ♦ Other materials may be available.

Figure 14.26 Spring-pin dimensions.

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14.4.4 Spiral spring pins (coiled spring pins)

The spiral spring pin was developed after the standard slotted spring pin in order to provide more shock resistance and a tighter fit in drilled holes. These pins are made for standard, light-duty, and heavy-duty applications and are produced in various materials to suit the application. Studies of slotted spring pins and spiral spring pins have found that the heavy-duty slotted spring pin will withstand more shock-loading cycles than the standard spiral spring pin. Figure 14.27 shows the sizes, dimensions, recommended hole sizes, and double-shear values for these pins.

14.4.5 Taper pins

The standard taper pin was used widely before the advent of spring pins and grooved pins. This pin type is still used in some industrial applications. Figure 14.28 shows the standard sizes and dimensions of taper pins.

14.4.6 Dowel pins (hardened and ground machine type)

The hardened and ground dowel pin is used widely in tooling applications and a wide range of indexing applications where great accuracy is required. Figure 14.29 shows the available standard sizes and dimensions of this important class of pin.

14.4.7 Grooved pins

The solid groove pin is one of the most popular fastening devices in use today. Its applications are limitless, and its use is economical, practical, and easy to implement. The hole diameter required for its application is not as critical as that for other solid pins. Seven standard styles or types are recognized as American national standards. Figure 14.30 shows the different types, sizes, and dimensions. Figure 14.31 shows the standard lengths. Figure 14.32 shows the recommended hole sizes.

14.4.8 Quick-release pins

The quick-release pin is available in many types and finds use in design applications where a quick release action of a fastened joint

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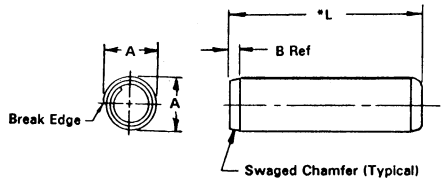

	A			B								
Basic Pin Diameter	Pin Diameter			Chamfer Length Ref.	Hole Size		Double Shear Load, Min., Lb ♦					
	Std Duty Max	Heavy Duty Max	Light Duty Max		Max	Min	Std Duty		Heavy Duty		Light Duty	
							1070, 1095 and 420	302	1070, 1095 and 420	302	1070, 1095 and 420	302
0.031	0.035	.....	.....	0.024	0.032	0.031	75	60	.....	.....	.....	.....
0.047	0.052	.....	.....	0.024	0.048	0.046	170	140	.....	.....	.....	.....
0.062	0.072	0.070	0.073	0.028	0.065	0.061	300	250	450	350	.....	135
0.078	0.088	0.086	0.089	0.032	0.081	0.077	475	400	700	550	.....	225
0.094	0.105	0.103	0.106	0.038	0.097	0.093	700	550	1,000	800	375	300
0.109	0.120	0.118	0.121	0.038	0.112	0.108	950	750	1,400	1,125	525	425
0.125	0.138	0.136	0.139	0.044	0.129	0.124	1,250	1,000	2,100	1,700	675	550
0.156	0.171	0.168	0.172	0.048	0.160	0.155	1,925	1,550	3,000	2,400	1,100	875
0.188	0.205	0.202	0.207	0.055	0.192	0.185	2,800	2,250	4,400	3,500	1,500	1,200
0.219	0.238	0.235	0.240	0.065	0.224	0.217	3,800	3,000	5,700	4,600	2,100	1,700
0.250	0.271	0.268	0.273	0.065	0.256	0.247	5,000	4,000	7,700	6,200	2,700	2,200
0.312	0.337	0.334	0.339	0.080	0.319	0.308	7,700	6,200	11,500	9,200	4,440	3,500
0.375	0.403	0.400	0.405	0.095	0.383	0.370	11,200	9,000	17,600	14,000	6,000	5,000
0.438	0.469	0.466	0.471	0.095	0.446	0.431	15,200	13,000	22,500	18,000	8,400	6,700
0.500	0.535	0.532	0.537	0.110	0.510	0.493	20,000	16,000	30,000	24,000	11,000	8,800
0.625	0.661	0.658	.....	0.125	0.635	0.618	31,000	25,000	46,000	37,000	.....	.....
0.750	0.787	0.784	.....	0.150	0.760	0.743	45,000	36,000	66,000	53,000	.....	.....

Figure 14.27 Spiral-spring-pin dimensions.

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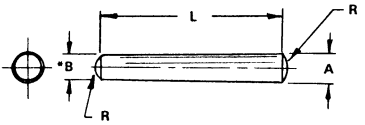

Pin Size Number and Basic Pin Dia		A Major Diameter (Large end) Commercial Class Max	Min	Precision Class Max	Min	R End Crown Radius Maximum
7/0	0.0625	0.0638	0.0618	0.0635	0.0625	0.072
6/0	0.0780	0.0793	0.0773	0.0790	0.0780	0.088
5/0	0.0940	0.0953	0.0933	0.0950	0.0940	0.104
4/0	0.1090	0.1103	0.1083	0.1100	0.1090	0.119
3/0	0.1250	0.1263	0.1243	0.1260	0.1250	0.135
2/0	0.1410	0.1423	0.1403	0.1420	0.1410	0.151
0	0.1560	0.1573	0.1553	0.1570	0.1560	0.166
1	0.1720	0.1733	0.1713	0.1730	0.1720	0.182
2	0.1930	0.1943	0.1923	0.1940	0.1930	0.203
3	0.2190	0.2203	0.2183	0.2200	0.2190	0.229
4	0.2500	0.2513	0.2493	0.2510	0.2500	0.260
5	0.2890	0.2903	0.2883	0.2900	0.2890	0.299
6	0.3410	0.3423	0.3403	0.3420	0.3410	0.351
7	0.4090	0.4103	0.4083	0.4100	0.4090	0.419
8	0.4920	0.4933	0.4913	0.4930	0.4920	0.502
9	0.5910	0.5923	0.5903	0.5920	0.5910	0.601
10	0.7060	0.7073	0.7053	0.7070	0.7060	0.716
11	0.8600	0.8613	0.8593	.....	.....	0.870
12	1.0320	1.0333	1.0313	.....	.....	1.042
13	1.2410	1.2423	1.2403	.....	.....	1.251
14	1.5210	1.5223	1.5203	.....	.....	1.531

* B dimension varies per length. Length L to be selected from manufacturer's catalogs.

Figure 14.28 Taper-pin dimensions.

or part is required. Most of these types of pins contain a push-button release action that allows the pin to be removed by a straight pulling action after the release button is pressed. The quick-release pin series is available in carbon steel, alloy steels, and stainless steels. Applications include tool engineering, aerospace vehicles, and many other applications where a strong, quick-release fastener is required. The quick-release pin is normally used for shear loading applications only.

(Text continued on page 903.)

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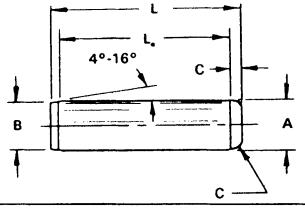

Nominal Diameter	Pin Diameter - A Standard Series Basic	Max	Min	Oversize Series Basic	Max	Min	B Point Dia Max	Min	C Crown Radius Max	Min	Double Shear Load, Lb Carbon or Alloy Steel
0.0625	0.0627	0.0628	0.0626	0.0635	0.0636	0.0634	0.058	0.048	0.020	0.008	800
0.0781	0.0783	0.0784	0.0782	0.0791	0.0792	0.0790	0.074	0.064	0.026	0.010	1,240
0.0938	0.0940	0.0941	0.0939	0.0948	0.0949	0.0947	0.089	0.079	0.031	0.012	1,800
0.1250	0.1252	0.1253	0.1251	0.1260	0.1261	0.1259	0.120	0.110	0.041	0.016	3,200
0.1562	0.1564	0.1565	0.1563	0.1572	0.1573	0.1571	0.150	0.140	0.052	0.020	5,000
0.1875	0.1877	0.1878	0.1876	0.1885	0.1886	0.1884	0.180	0.170	0.062	0.023	7,200
0.2500	0.2502	0.2503	0.2501	0.2510	0.2511	0.2509	0.240	0.230	0.083	0.031	12,800
0.3125	0.3127	0.3128	0.3126	0.3135	0.3136	0.3134	0.302	0.290	0.104	0.039	20,000
0.3750	0.3752	0.3753	0.3751	0.3760	0.3761	0.3759	0.365	0.350	0.125	0.047	28,700
0.4375	0.4377	0.4378	0.4376	0.4385	0.4386	0.4384	0.424	0.409	0.146	0.055	39,100
0.5000	0.5002	0.5003	0.5001	0.5010	0.5011	0.5009	0.486	0.471	0.167	0.063	51,000
0.6250	0.6252	0.6253	0.6251	0.6260	0.6261	0.6259	0.611	0.595	0.208	0.078	79,800
0.7500	0.7502	0.7503	0.7501	0.7510	0.7511	0.7509	0.735	0.715	0.250	0.094	114,000
0.8750	0.8752	0.8753	0.8751	0.8760	0.8761	0.8759	0.860	0.840	0.293	0.109	156,000
1.0000	1.0002	1.0003	1.0001	1.0010	1.0011	1.0009	0.980	0.960	0.333	0.125	204,000

Note: Sizes 0.0781 and 0.1562 diameter not recommended for new design.
L = Total pin length; L_e = Length of engagement.
Dowel pins listed are available in nominal lengths from 0.1875 to 6.000 inches.
Consult the manufacturer's catalogs for available lengths.

Figure 14.29 Dowel-pin dimensions.

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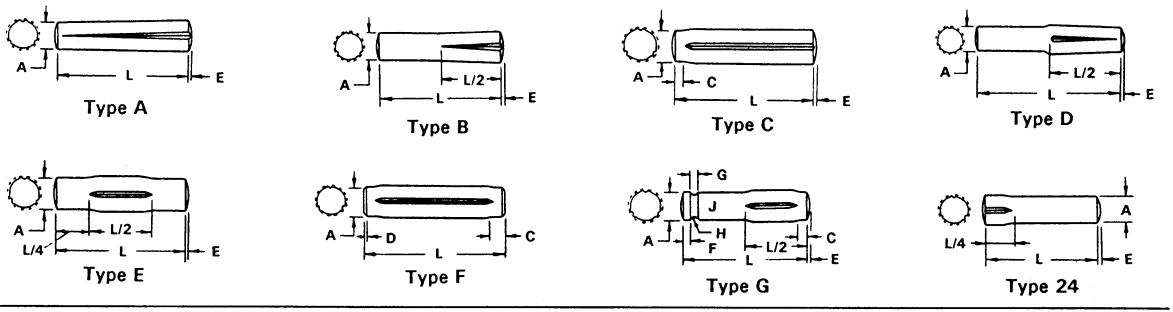

Basic Pin Diameter	A Max	C Ref.	D Min.	E Max	F Min.	G Max.	H Ref.	J Max
0.0312	0.0312	0.015	.....	.....	.....	.....	.....	.....
0.0469	0.0469	0.031	.....	.....	.....	.....	.....	.....
0.0625	0.0625	0.031	0.016	0.0115	.....	.....	.....	.....
0.0781	0.0781	0.031	0.016	0.0137	.....	.....	.....	.....
0.0938	0.0938	0.031	0.016	0.0141	0.028	0.041	0.016	0.067
0.1094	0.1094	0.031	0.016	0.0160	0.028	0.041	0.016	0.082
0.1250	0.1250	0.031	0.016	0.0180	0.059	0.041	0.031	0.088
0.1563	0.1563	0.062	0.031	0.0220	0.059	0.057	0.031	0.109
0.1875	0.1875	0.062	0.031	0.0230	0.059	0.057	0.031	0.130
0.2188	0.2188	0.062	0.031	0.0270	0.091	0.072	0.047	0.151
0.2500	0.2500	0.062	0.031	0.0310	0.091	0.072	0.047	0.172
0.3125	0.3125	0.094	0.047	0.0390	0.122	0.104	0.062	0.214
0.3750	0.3750	0.094	0.047	0.0440	0.122	0.135	0.062	0.255
0.4375	0.4375	0.094	0.047	0.0520	0.185	0.135	0.094	0.298
0.5000	0.5000	0.094	0.047	0.0570	0.185	0.135	0.094	0.317

Figure 14.30 Grooved-pin dimensions.

Nominal Length	Nominal Size														
	1/32	3/64	1/16	5/64	3/32	7/64	1/8	5/32	3/16	7/32	1/4	5/16	3/8	7/16	1/2
1/8	Y	Y	Y												
1/4	Y	Y	Y	Y	Y	Y	Y								
3/8	Y	Y	Y	Y	X	X	X	X	X						
1/2	Y	Y	Y	Y	X	X	X	X	X	X	X				
5/8		Y	Y	Y	X	X	X	X	X	X	X	X			
3/4			Y	Y	X	X	X	X	X	X	X	X	X		
7/8			Y	Y	X	X	X	X	X	X	X	X	X	X	
1			Y	Y	X	X	X	X	X	X	X	X	X	X	X
1-1/4					X	X	X	X	X	X	X	X	X	X	X
1-1/2							X	X	X	X	X	X	X	X	X
1-3/4								X	X	X	X	X	X	X	X
2								X	X	X	X	X	X	X	X
2-1/4									X	X	X	X	X	X	X
2-1/2										X	X	X	X	X	X
2-3/4										X	X	X	X	X	X
3										X	X	X	X	X	X
3-1/4											X	X	X	X	X
3-1/2												X	X	X	X
3-3/4													X	X	X
4													X	X	X
4-1/4													X	X	X
4-1/2														X	X

Note: Carbon steel pins are normally available in the marked sizes by X and Y. X designates all types of pins; Y designates all types except type G. Other lengths may be available from different manufacturers.

Figure 14.31 Sizes and lengths of standard grooved pins.

Recommended Hole Sizes For Grooved Pins			
Nominal Pin Size	Drill Size	Hole Diameter	
		Max	Min
1/32	1/32	0.0324	0.0312
3/64	3/64	0.0482	0.0469
1/16	1/16	0.0640	0.0625
5/64	5/64	0.0798	0.0781
3/32	3/32	0.0956	0.0938
7/64	7/64	0.1113	0.1094
1/8	1/8	0.1271	0.1250
5/32	5/32	0.1587	0.1563
3/16	3/16	0.1903	0.1875
7/32	7/32	0.2219	0.2188
1/4	1/4	0.2534	0.2500
5/16	5/16	0.3166	0.3125
3/8	3/8	0.3797	0.3750
7/16	7/16	0.4428	0.4375
1/2	1/2	0.5060	0.5000

Figure 14.32 Hole sizes for grooved pins.

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Fastening and Joining Techniques and Hardware

14.5 Retaining Rings

Retaining rings have many uses in the design and maintenance of modern equipment, including

- Shaft retention
- Bearing retention
- Retention of parts on shafts
- Spring retention
- Vertical and horizontal shaft support

The standard retaining ring is normally made of spring steel, although other materials such as beryllium-copper alloys and stainless steels are sometimes used. Figure 14.33 shows some of the main retaining types.

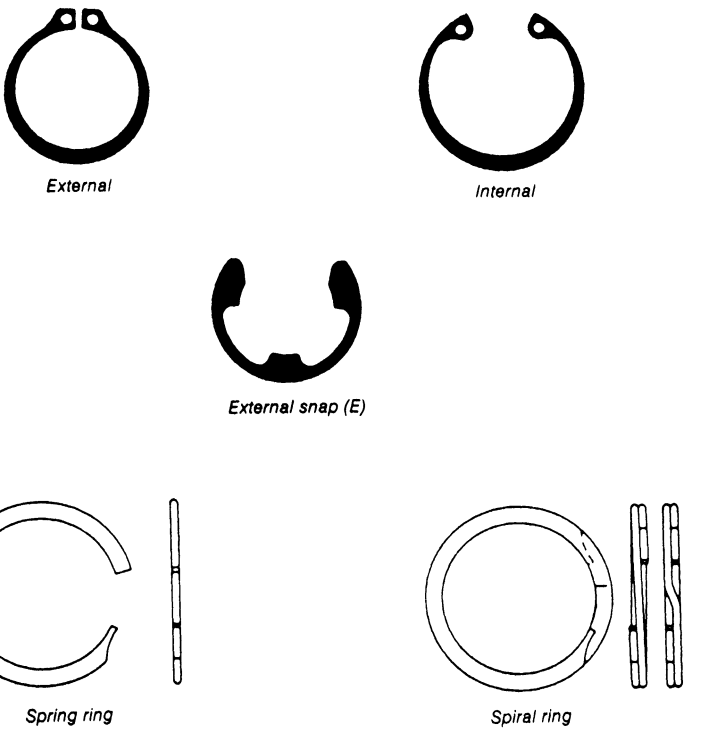

Figure 14.33 Retaining-ring styles.

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The allowable thrust loads for each type of retaining ring must be obtained from the retaining ring manufacturers' handbooks. The calculation procedures for various applications are also shown in these handbooks. There are at least 25 to 30 different types of retaining rings. The critical dimensions for machining the grooves that hold the retaining ring in place are also obtained from the manufacturers' handbooks. Figure 14.34 shows a typical page from the Waldes retaining ring handbook. This sample page is for the 5100 external type ring, and the typical machining dimensions for the retaining groove may be seen under "Groove Dimensions" in the table. Dimensions and application data are also shown.

Note that electroplating thickness can interfere with the proper functioning of the ring in the groove. Overplating can cause the ring to come out of the retaining groove during operation of the mechanism on which the ring is used. Therefore, specify a maximum plating thickness of 0.0002 in (0.2 mil) or allow additional clearance for the ring in the groove when the part is to be electroplated.

Figure 14.35 shows a retaining-ring interchangeability chart for various manufacturers and also lists the appropriate military standard numbers.

14.5.1 X-washers (split washers)

An X-washer is a unique type of retaining ring. It is used in applications similar to those for the standard spring retaining ring except that it may be installed with a pair of common pliers, as shown in Fig. 14.36. The dimensions and sizes of the presently available X-washer series are also shown in this figure. The X-washer is sometimes called a *split washer* and may be listed as such in fastener catalogs, although that is an incorrect name.

An X-washer normally is used for a one-time-only application. Once the washer is installed on a shaft and removed with pliers, it should not be reused. Although applicable only for one-time installations, these devices are suitable and economical for many applications in product design and manufacturing. The fact that these washers may be installed and removed with common pliers, and not special tools, is an asset in their application.

14.6 Set-Collars, Clamp-Collars, and Split-Collars

These devices have many uses in product design and manufacturing. They are used to retain shafts, to withstand high-thrust loads, and to space parts, and they are often welded to plate cams, plate

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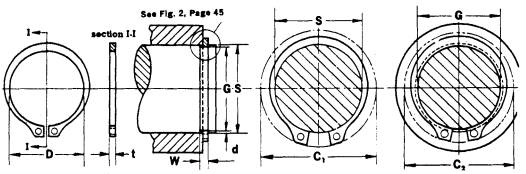

SHAFT DIAMETER			MIL-R-21248 MS 16624	TRUARC RING DIMENSIONS					GROOVE DIMENSIONS					APPLICATION DATA			
				Thickness t applies only to unplated rings. For plated and stainless steel (Type H) rings, add .002" to the listed maximum thickness. Maximum ring thickness will be at least .0002" less than the listed minimum groove width (W).					T.I.R. (total indicator reading) is the maximum allowable deviation of concentricity between groove and shaft.					CLEARANCE DIAMETER		ALLOW. THRUST LOAD (lbs.) Sharp Corner Abutment	
																RINGS (standard material)	GROOVES (Cold Rolled steel shafts)
Dec. equiv. inch	Approx fract. equiv. inch	Approx. mm	EXTERNAL SERIES 5100	FREE DIA.		THICKNESS		Approx. weight per 1000 pieces	DIAMETER		WIDTH		Nominal groove depth	When sprung over shaft S	When sprung into groove G	Safety factor = 4	Safety factor = 2
																Important! See Page 25	
S	S	S	size — no.	D	tol.	t	tol.	lbs.	G	tol.	W	tol.	d	C_1	C_2	P_r	P_g
.125	1/8	3.2	▲ 5100-12	.112		.010	±.001	.018	.117		.012		.004	.222	.214	110	35
.156	5/32	4.0	▲ 5100-15	.142		.010		.037	.146		.012		.005	.270	.260	130	55
.188	3/16	4.8	▲ 5100-18	.168		.015		.059	.175	±.0015 .0015 T.I.R.	.018	+.002 −.000	.006	.298	.286	240	80
.197	— —	5.0	▲ 5100-19	.179	+.002 −.004	.015		.063	.185		.018		.006	.319	.307	250	85
.219	7/32	5.6	▲ 5100-21	.196		.015		.074	.205		.018		.007	.338	.324	280	110
.236	15/64	6.0	▲ 5100-23	.215		.015		.086	.222		.018		.007	.355	.341	310	120
.250	1/4	6.4	• 5100-25	.225		.025		.21	.230		.029		.010	.45	.43	590	175
.276	— —	7.0	5100-27	.250		.025		.23	.255		.029		.010	.48	.46	650	195
.281	9/32	7.1	• 5100-28	.256		.025		.24	.261		.029		.010	.49	.47	660	200
.312	5/16	7.9	• 5100-31	.281		.025		.27	.290		.029		.011	.54	.52	740	240
.344	11/32	8.7	5100-34	.309		.025		.31	.321	±.002 .002 T.I.R.	.029		.011	.57	.55	800	265
.354	— —	9.0	5100-35	.320		.025		.35	.330		.029		.012	.59	.57	820	300
.375	3/8	9.5	• 5100-37	.338	+.002 −.005	.025		.39	.352		.029		.012	.61	.59	870	320
.394	— —	10.0	5100-39	.354		.025		.42	.369		.029		.012	.62	.60	940	335
.406	13/32	10.3	5100-40	.366		.025		.43	.382		.029		.012	.63	.61	950	350
.438	7/16	11.1	• 5100-43	.395		.025		.50	.412		.029		.013	.66	.64	1020	400
.469	15/32	11.9	5100-46	.428		.025		.54	.443		.029		.013	.68	.66	1100	450
.500	1/2	12.7	• 5100-50	.461		.035		.91	.468	±.002 .004 T.I.R.	.039		.016	.77	.74	1650	550
.551	— —	14.0	5100-55	.509		.035		.90	.519		.039		.016	.81	.78	1800	600
.562	9/16	14.3	• 5100-56	.521		.035		1.1	.530		.039	+.003 −.000	.016	.82	.79	1850	650
.594	19/32	15.1	5100-59	.550		.035	±.002	1.2	.559		.039		.017	.86	.83	1950	750
.625	5/8	15.9	• 5100-62	.579		.035		1.3	.588		.039		.018	.90	.87	2060	800
.669	— —	17.0	5100-66	.621		.035		1.4	.629		.039		.020	.93	.89	2200	950
.672	43/64	17.1	5100-66	.621		.035		1.4	.631		.039		.020	.93	.89	2200	950
.688	11/16	17.5	• 5100-68	.635	+.005 −.010	.042		1.8	.646	±.003 .004 T.I.R.	.046		.021	1.01	.97	3400	1000
.750	3/4	19.0	• 5100-75	.693		.042		2.1	.704		.046		.023	1.09	1.05	3700	1200
.781	25/32	19.8	5100-78	.722		.042		2.2	.733		.046		.024	1.12	1.08	3900	1300
.812	13/16	20.6	5100-81	.751		.042		2.5	.762		.046		.025	1.15	1.10	4000	1450
.875	7/8	22.2	5100-87	.810		.042		2.8	.821		.046		.027	1.21	1.16	4300	1650
.938	15/16	23.8	5100-93	.867		.042		3.1	.882		.046		.028	1.34	1.29	4650	1850
.984	63/64	25.0	5100-98	.910		.042		3.5	.926		.046		.029	1.39	1.34	4850	2000
1.000	1	25.4	5100-100	.925		.042		3.6	.940		.046		.030	1.41	1.35	4950	2100
1.023	— —	26.0	5100-102	.946		.042		3.9	.961		.046		.031	1.43	1.37	5050	2250
1.062	1 1/16	27.0	5100-106	.982		.050		4.8	.998		.056		.032	1.50	1.44	6200	2400
1.125	1 1/8	28.6	5100-112	1.041		.050		5.1	1.059		.056		.033	1.55	1.49	6600	2600
1.188	1 3/16	30.2	5100-118	1.098		.050		5.6	1.118		.056		.035	1.61	1.54	7000	2950
1.250	1 1/4	31.7	5100-125	1.156	+.010 −.015	.050		5.9	1.176	±.004 .005 T.I.R	.056		.037	1.69	1.62	7350	3250
1.312	1 5/16	33.3	5100-131	1.214		.050		6.8	1.232		.056		.040	1.75	1.67	7750	3700
1.375	1 3/8	34.9	5100-137	1.272		.050		7.2	1.291		.056		.042	1.80	1.72	8100	4100
1.438	1 7/16	36.5	5100-143	1.333		.050		8.1	1.350		.056		.044	1.87	1.79	8500	4500
1.500	1 1/2	38.1	5100-150	1.387		.050		9.0	1.406		.056	+.004 −.000	.047	1.99	1.90	8800	5000
1.562	1 9/16	39.7	5100-156	1.446		.062		12.4	1.468		.068		.047	2.10	2.01	11400	5200
1.625	1 5/8	41.3	5100-162	1.503		.062		13.2	1.529		.068		.048	2.17	2.08	11850	5500
1.688	1 11/16	42.9	5100-168	1.560		.062		14.8	1.589		.068		.049	2.24	2.15	12350	5850
1.750	1 3/4	44.4	5100-175	1.618		.062	±.003	15.3	1.650	±.005 .005 T.I.R	.068		.050	2.31	2.21	12800	6200
1.772	— —	45.0	5100-177	1.637	+.013 −.020	.062		15.4	1.669		.068		.051	2.33	2.23	12950	6400
1.812	1 13/16	46.0	5100-181	1.675		.062		16.2	1.708		.068		.052	2.38	2.28	13250	6650
1.875	1 7/8	47.6	5100-187	1.735		.062		17.3	1.769		.068		.053	2.44	2.34	13700	7000
1.969	1 31/32	50.0	5100-196	1.819		.062		18.0	1.857		.068		.056	2.54	2.43	14350	7800
2.000	2	50.8	5100-200	1.850		.062		19.0	1.886		.068		.057	2.55	2.44	14600	8050

Figure 14.34 Sample Truarc ring data sheet.

sprockets, and indexing plates to form a hub by which the part is retained on a shaft. The standard set-collar is simply a machined ring with set screws that hold the ring on a shaft or cylindrical end of a part. Figure 14.37 shows the standard set-collar sizes and dimensions. These collars normally are made from low-carbon steel with zinc plating as a finish.

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	Roto Clip	Waldes	I.R.R.	Anderton	Mil Standard
	E	5133	1000	1500	16633
	BE	5131	1001	1501	16634
	RE	5144	1200	1540	3215
	C	5103	2000	1800	16632
	HO	5000	3000	1300	16625
	BHO	5001	3001	1301	16629
	VHO	5002	—	1302	16631
	SH	5100	3100	1400	16624
	BSH	5101	3101	1401	16628
	VSH	5102	—	1402	16630
	HOI	5008	4000	1308	16627
	SHI	5108	4100	1408	16626
	SHF	5555	7100	1440	90707
	SHR	5160	—	1460	3217
	SHM	5560	—	—	—

Figure 14.35 Retaining-ring interchangeability table.

Clamp-collars are similar to set-collars, except that they have a slit through one wall and are clamped on a shaft by tightening the clamp screw provided on the collar. These types of collars are also made with internal threads for adjustment and a more positive clamping force. Clamp-collars normally are made of carbon steels,

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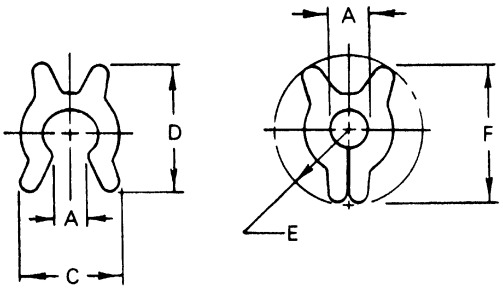

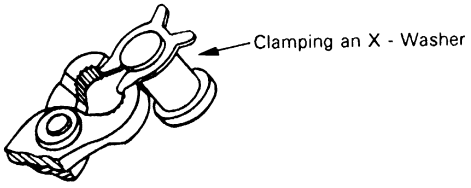

X - Washer Dimensions

A	B*	C	D	E	F
.086	.025	.320	.406	.210	.406
.098	.055	.364	.490	.297	.475
.130	.055	.430	.575	.359	.556
.164	.065	.523	.687	.422	.665
.190	.065	.593	.745	.437	.730
.222	.075	.622	.776	.469	.775
.256	.075	.698	.905	.500	.890
.285	.075	.822	.986	.563	.984
.317	.089	.872	1.100	.609	1.078
.347	.089	.948	1.190	.688	1.188
.381	.089	1.060	1.297	.797	1.281

NOTE: B* = thickness, inches

Figure 14.36 X-washer dimensional sizes. X-washers are often called *split washers.*

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DIMENSIONS			
BORE	O. D.	WIDTH	SET SCREW
3/16	7/16	1/4	8-32
1/4	1/2	9/32	10-32
5/16	5/8	11/32	10-32
3/8	3/4	3/8	1/4-20
7/16	7/8	7/16	1/4-20
1/2	1"	7/16	1/4-20
9/16	1"	7/16	1/4-20
5/8	1-1/8	1/2	5/16-18
11/16	1-1/4	9/16	5/16-18
3/4	1-1/4	9/16	5/16-18
13/16	1-5/16	9/16	5/16-18
7/8	1-1/2	9/16	5/16-18
15/16	1-5/8	9/16	5/16-18
1"	1-5/8	5/8	5/16-18
1-1/16	1-3/4	5/8	5/16-18
1-1/8	1-3/4	5/8	5/16-18
1-3/16	2"	11/16	3/8-16
1-1/4	2"	11/16	3/8-16
1-5/16	2-1/8	11/16	3/8-16
1-3/8	2-1/8	3/4	3/8-16
1-7/16	2-1/4	3/4	3/8-16
1-1/2	2-1/4	3/4	3/8-16
1-9/16	2-1/2	13/16	3/8-16
1-5/8	2-1/2	13/16	3/8-16
1-11/16	2-1/2	13/16	3/8-16
1-3/4	2-3/4	7/8	1/2-13
1-13/16	2-3/4	7/8	1/2-13
1-7/8	2-3/4	7/8	1/2-13
1-15/16	3"	7/8	1/2-13
2"	3"	7/8	1/2-13
2-1/16	3"	7/8	1/2-13
2-1/8	3"	7/8	1/2-13
2-3/16	3-1/4	15/16	1/2-13
2-1/4	3-1/4	15/16	1/2-13
2-5/16	3-1/4	15/16	1/2-13
2-3/8	3-1/4	15/16	1/2-13
2-7/16	3-1/2	1"	1/2-13
2-1/2	3-1/2	1"	1/2-13
2-9/16	3-3/4	1-1/8	1/2-13
2-5/8	3-3/4	1-1/8	1/2-13
2-11/16	4"	1-1/8	1/2-13
2-3/4	4"	1-1/8	1/2-13
2-13/16	4-1/4	1-1/8	1/2-13
2-7/8	4-1/4	1-1/8	1/2-13
2-15/16	4-1/4	1-1/8	1/2-13
3"	4-1/4	1-1/8	1/2-13

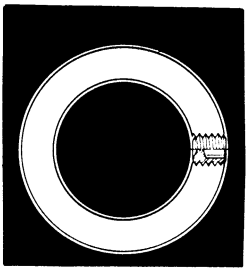

Figure 14.37 Set-collars. *(Ruland, Inc.)*

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aluminum alloys, and stainless steels. Figure 14.38 shows the sizes and dimensions of standard clamp-collars, and Fig. 14.39 shows the data for the internally threaded clamp-collar series.

Split-collars and threaded split-collars are also available and used widely in machine design. The data for these types of clamping collars are shown in Figs. 14.40 and 14.41.

Note: Figures 14.37 through 14.41 were extracted from the Ruland catalog of collars and couplings (Ruland Manufacturing Company, Inc., Watertown, MA 02172).

14.7 Machinery Bushings, Shims, and Arbor Spacers

14.7.1 Machinery bushings

Machinery bushings are a special form of flat washer commonly made of low-carbon mild steel. They are used as spacers between gears, pulleys, and sprockets and as filler spacers for parts mounted on shafts. These bushings are manufactured in the following gauges and diameters:

- 18 gauge, 0.048 in
- 14 gauge, 0.075 in
- 10 gauge, 0.134 in
- 3/16 in, 0.1875 in

Inside diameters range from 0.500 through 3.00 in.

14.7.2 Steel shims

Steel shims are thin steel rings with a plain center hole that are used for building up gears and bearings and to provide proper clearance between mating parts. Figure 14.42 lists the sizes and thicknesses normally available for steel shims.

14.7.3 Steel arbor spacers

Steel arbor spacers are thin steel rings with a keyway center hole that are used for accurately spacing milling cutters, slitter knives, and gang saws on keyway arbors. Steel shims and steel arbor spacers are made of AISI 1010, fully hardened, cold-rolled low-carbon steel. Figure 14.42 also lists the sizes and thicknesses of steel arbor spacers.

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DIMENSIONS			
BORE	O.D.	WIDTH	CLAMP SCREW
1/8	1/2	.235	4-40
3/16	9/16	.235	4-40
1/4	5/8	.281	4-40
5/16	11/16	.281	4-40
3/8	7/8	.343	6-32
7/16	15/16	.343	6-32
1/2	1-1/8	.406	8-32
9/16	1-1/4	.437	10-32
5/8	1-5/16	.437	10-32
11/16	1-3/8	.437	10-32
3/4	1-1/2	1/2	1/4-28
13/16	1-5/8	1/2	1/4-28
7/8	1-5/8	1/2	1/4-28
15/16	1-3/4	1/2	1/4-28
1	1-3/4	1/2	1/4-28
1-1/16	1-7/8	1/2	1/4-28
1-1/8	1-7/8	1/2	1/4-28
1-3/16	2-1/16	1/2	1/4-28
1-1/4	2-1/16	1/2	1/4-28
1-5/16	2-1/8	9/16	1/4-28
1-3/8	2-1/4	9/16	1/4-28
1-7/16	2-1/4	9/16	1/4-28
1-1/2	2-3/8	9/16	1/4-28
1-9/16	2-3/8	9/16	1/4-28
1-5/8	2-5/8	11/16	5/16-24
1-11/16	2-3/4	11/16	5/16-24
1-3/4	2-3/4	11/16	5/16-24
1-13/16	2-7/8	11/16	5/16-24
1-7/8	2-7/8	11/16	5/16-24
1-15/16	3	11/16	5/16-24
2	3	11/16	5/16-24
2-1/16	3-1/8	3/4	5/16-24
2-1/8	3-1/4	3/4	5/16-24
2-3/16	3-1/4	3/4	5/16-24
2-1/4	3-1/4	3/4	5/16-24
2-5/16	3-3/8	3/4	5/16-24
2-3/8	3-1/2	3/4	5/16-24
2-7/16	3-1/2	3/4	5/16-24
2-1/2	3-3/4	7/8	3/8-24
2-9/16	3-7/8	7/8	3/8-24
2-5/8	3-7/8	7/8	3/8-24
2-11/16	4	7/8	3/8-24
2-3/4	4	7/8	3/8-24
2-13/16	4-1/4	7/8	3/8-24
2-7/8	4-1/4	7/8	3/8-24
2-15/16	4-1/4	7/8	3/8-24
3	4-1/4	7/8	3/8-24

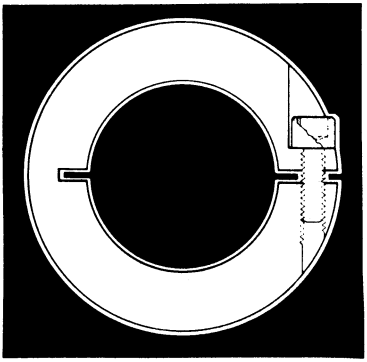

Figure 14.38 Clamp-collars. *(Ruland, Inc.)*

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DIMENSIONS			
THREADED BORE	O.D.	WIDTH	CLAMP SCREW
8-32	1/2	.235	4-40
10-24	9/16	.235	4-40
10-32	9/16	.235	4-40
1/4-20	5/8	.281	4-40
1/4-28	5/8	.281	4-40
5/16-18	11/16	.281	4-40
5/16-24	11/16	.281	4-40
3/8-16	7/8	.343	6-32
3/8-24	7/8	.343	6-32
7/16-14	15/16	.343	6-32
7/16-20	15/16	.343	6-32
1/2-13	1-1/8	.406	8-32
1/2-20	1-1/8	.406	8-32
5/8-11	1-5/16	.437	10-32
5/8-18	1-5/16	.437	10-32
3/4-10	1-1/2	1/2	1/4-28
3/4-16	1-1/2	1/2	1/4-28
7/8-9	1-5/8	1/2	1/4-28
7/8-14	1-5/8	1/2	1/4-28
1-8	1-3/4	1/2	1/4-28
1-12	1-3/4	1/2	1/4-28
1-14	1-3/4	1/2	1/4-28
1-1/8-7	1-7/8	1/2	1/4-28
1-1/8-12	1-7/8	1/2	1/4-28
1-1/4-7	2-1/16	1/2	1/4-28
1-1/4-12	2-1/16	1/2	1/4-28
1-3/8-6	2-1/4	9/16	1/4-28
1-3/8-12	2-1/4	9/16	1/4-28
1-1/2-6	2-3/8	9/16	1/4-28
1-1/2-12	2-3/8	9/16	1/4-28
1-3/4-16	2-3/4	11/16	5/16-24
2"-12	3	11/16	5/16-24

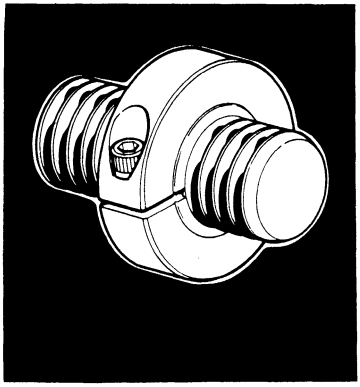

Figure 14.39 Threaded clamp-collars. *(Ruland, Inc.)*

14.8 Specialty Fasteners

The specialty fastener component lines available today are great in numbers and types. This section will detail only those specialty fasteners which have become common and which are used widely in new product design and manufacturing.

A partial listing of some of the common specialty fasteners would include

- Acorn nuts
- Floating nuts

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DIMENSIONS			
BORE	O.D.	WIDTH	CLAMP SCREW
1/8	1/2	.235	4-40
3/16	9/16	.235	4-40
1/4	5/8	.281	4-40
5/16	11/16	.281	4-40
3/8	7/8	.343	6-32
7/16	15/16	.343	6-32
1/2	1-1/8	.406	8-32
9/16	1-1/4	.437	10-32
5/8	1-5/16	.437	10-32
11/16	1-3/8	.437	10-32
3/4	1-1/2	1/2	1/4-28
13/16	1-5/8	1/2	1/4-28
7/8	1-5/8	1/2	1/4-28
15/16	1-3/4	1/2	1/4-28
1	1-3/4	1/2	1/4-28
1-1/16	1-7/8	1/2	1/4-28
1-1/8	1-7/8	1/2	1/4-28
1-3/16	2-1/16	1/2	1/4-28
1-1/4	2-1/16	1/2	1/4-28
1-5/16	2-1/8	9/16	1/4-28
1-3/8	2-1/4	9/16	1/4-28
1-7/16	2-1/4	9/16	1/4-28
1-1/2	2-3/8	9/16	1/4-28
1-9/16	2-3/8	9/16	1/4-28
1-5/8	2-5/8	11/16	5/16-24
1-11/16	2-3/4	11/16	5/16-24
1-3/4	2-3/4	11/16	5/16-24
1-13/16	2-7/8	11/16	5/16-24
1-7/8	2-7/8	11/16	5/16-24
1-15/16	3	11/16	5/16-24
2	3	11/16	5/16-24
2-1/16	3-1/8	3/4	5/16-24
2-1/8	3-1/4	3/4	5/16-24
2-3/16	3-1/4	3/4	5/16-24
2-1/4	3-1/4	3/4	5/16-24
2-5/16	3-3/8	3/4	5/16-24
2-3/8	3-1/2	3/4	5/16-24
2-7/16	3-1/2	3/4	5/16-24
2-1/2	3-3/4	7/8	3/8-24
2-9/16	3-7/8	7/8	3/8-24
2-5/8	3-7/8	7/8	3/8-24
2-11/16	4	7/8	3/8-24
2-3/4	4	7/8	3/8-24
2-13/16	4-1/4	7/8	3/8-24
2-7/8	4-1/4	7/8	3/8-24
2-15/16	4-1/4	7/8	3/8-24
3	4-1/4	7/8	3/8-24

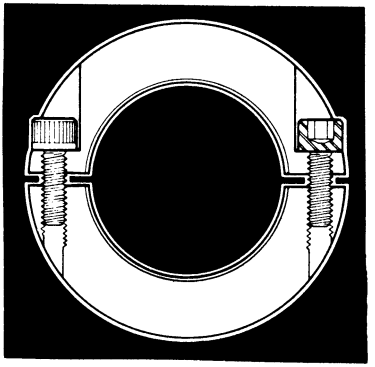

Figure 14.40 Split-collars. *(Ruland, Inc.)*

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DIMENSIONS			
BORE	O.D.	WIDTH	CLAMP SCREW
8-32	1/2	.235	4-40
10-24	9/16	.235	4-40
10-32	9/16	.235	4-40
1/4-20	5/8	.281	4-40
1/4-28	5/8	.281	4-40
5/16-18	11/16	.281	4-40
5/16-24	11/16	.281	4-40
3/8-16	7/8	.343	6-32
3/8-24	7/8	.343	6-32
7/16-14	15/16	.343	6-32
7/16-20	15/16	.343	6-32
1/2-13	1-1/8	.406	8-32
1/2-20	1-1/8	.406	8-32
5/8-11	1-5/16	.437	10-32
5/8-18	1-5/16	.437	10-32
3/4-10	1-1/2	1/2	1/4-28
3/4-16	1-1/2	1/2	1/4-28
7/8-9	1-5/8	1/2	1/4-28
7/8-14	1-5/8	1/2	1/4-28
1-8	1-3/4	1/2	1/4-28
1-12	1-3/4	1/2	1/4-28
1-14	1-3/4	1/2	1/4-28
1-1/8-7	1-7/8	1/2	1/4-28
1-1/8-12	1-7/8	1/2	1/4-28
1-1/4-7	2-1/16	1/2	1/4-28
1-1/4-12	2-1/16	1/2	1/4-28
1-3/8-6	2-1/4	9/16	1/4-28
1-3/8-12	2-1/4	9/16	1/4-28
1-1/2-6	2-3/8	9/16	1/4-28
1-1/2-12	2-3/8	9/16	1/4-28
1-3/4-16	2-3/4	11/16	5/16-24
2"-12	3	11/16	5/16-24

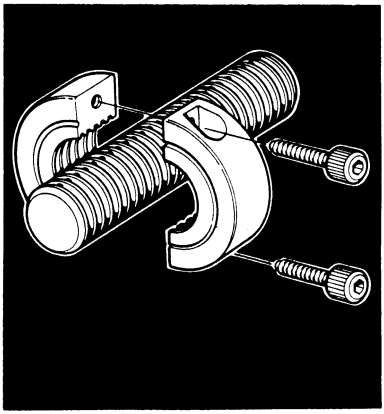

Figure 14.41 Split threaded clamp-collars. *(Ruland, Inc.)*

- Plastic bolts
- Split lock nuts
- SEMs
- Weld nuts
- Various plastic washers
- Sealing washers
- T-slot nuts and bolts
- Push nuts (pal nuts)

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Sizes and Thicknesses of Steel Shims - (Inches)

ID	OD	Thickness Ranges
0.375	0.625	0.001 0.002 0.003 0.004 0.005 0.006 0.007 0.008 0.010 0.012 0.015 0.020 0.025 0.031 0.047
0.500	0.750	0.0062 0.093 0.125 (These thicknesses available in all ID and OD sizes)
0.625	1.000	
0.750	1.125	
0.875	1.375	
1.000	1.500	
1.125	1.625	
1.250	1.750	
1.375	1.875	
1.500	2.125	
1.750	2.750	
2.000	2.750	

Sizes and Thicknesses of Steel Arbor Spacers - (Inches)

ID	OD	Thickness Ranges
0.500	0.750	0.001 0.002 0.003 0.004 0.005 0.006 (These thicknesses available for diameters listed)
0.625	1.000	
0.750	1.125	
0.875	1.375	
1.000	1.500	
1.250	1.750	
1.500	2.125	
2.000	2.250	
0.750	1.125	0.007 0.008 0.010 0.012 0.015 0.020 (These thicknesses available for diameters listed)
0.875	1.375	
1.000	1.500	
1.250	1.750	
1.500	2.125	
2.000	2.750	
1.000	1.500	0.025 0.031 0.047 0.062 0.093 0.125 (These thicknesses available for diameters listed)
1.250	1.750	
1.500	2.125	
2.000	2.750	

Figure 14.42 Steel shims and arbor spacers.

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Fastening and Joining Techniques and Hardware

- Various types of weld studs
- Sheet metal nuts
- Nylok bolts
- Flanged "whiz" bolts
- Turnbuckles

14.8.1 Specialty fasteners in common use

Figure 14.43 shows the different types of SEMs (screw and captive washer assemblies) available today. Note that on the SEM, the screw is either thread-forming or thread-tapping. This makes this class of fastener useful and economical in rapid-assembly applications such as automotive equipment manufacturing. SEMs are specified in ANSI Standard ANSI/ASME B18.13.

Figure 14.44 shows some of the widely used Tinnerman types of speed nuts, which are made of high-carbon, spring-tempered steel. These types of speed nuts are produced in sizes from 6-32 through 5/16-18 or larger in special cases. The Tinnerman type U and J nuts are used widely to fasten sheet metal screw covers onto sheet metal enclosures. The flat and round types are used on through-bolt sheet metal applications, such as automotive equipment and electronic chassis work. These are economical, efficient fasteners whose applications are limitless.

Another specialty type of fastener that is used widely is the swage nut. The swage nut is produced in several different styles, one of which is shown in Fig. 14.45*a*. The swage nut is extremely useful in applications where the thread cannot be produced efficiently or effectively in a parent metal that must be fastened to another part. Swage nuts are used in switch-gear equipment where copper bus bars are fastened together, and it is not practical to tap the soft copper bars for bolting. These nuts are also used on thin sheet metal parts where a strong joint is required, and not enough material thickness is available for tapping the sheet metal. The swage nut normally is made from carbon steel with zinc or cadmium plating, stainless steels, and aluminum alloys. Figure 14.45*a* shows a typical PEM-type nut.

The Rivnut and Plusnut, which are produced by B. F. Goodrich Company, are shown in Fig. 14.45*b* and *c*. These types of "blind" fasteners have countless applications in industry and are also produced with sealed ends for liquid-proofing applications. The Rivnut is used widely in the aerospace industry.

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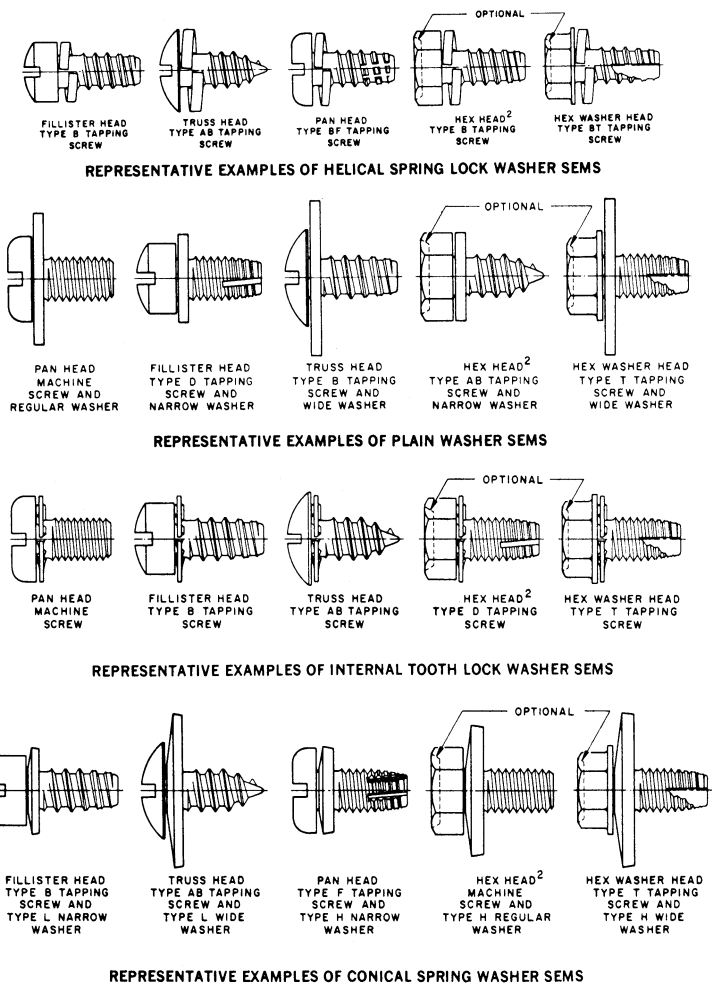
SEMS - by SHAKEPROOF
(Pre-assembled lock washer and screw units)
OPTIONAL
FILLISTER HEAD TYPE B TAPPING SCREW
TRUSS HEAD TYPE AB TAPPING SCREW
PAN HEAD TYPE BF TAPPING SCREW
HEX HEAD[2] TYPE B TAPPING SCREW
HEX WASHER HEAD TYPE BT TAPPING SCREW
REPRESENTATIVE EXAMPLES OF HELICAL SPRING LOCK WASHER SEMS
OPTIONAL
PAN HEAD MACHINE SCREW AND REGULAR WASHER
FILLISTER HEAD TYPE D TAPPING SCREW AND NARROW WASHER
TRUSS HEAD TYPE B TAPPING SCREW AND WIDE WASHER
HEX HEAD[2] TYPE AB TAPPING SCREW AND NARROW WASHER
HEX WASHER HEAD TYPE T TAPPING SCREW AND WIDE WASHER
REPRESENTATIVE EXAMPLES OF PLAIN WASHER SEMS
OPTIONAL
PAN HEAD MACHINE SCREW
FILLISTER HEAD TYPE B TAPPING SCREW
TRUSS HEAD TYPE AB TAPPING SCREW
HEX HEAD[2] TYPE D TAPPING SCREW
HEX WASHER HEAD TYPE T TAPPING SCREW
REPRESENTATIVE EXAMPLES OF INTERNAL TOOTH LOCK WASHER SEMS
OPTIONAL
FILLISTER HEAD TYPE B TAPPING SCREW AND TYPE L NARROW WASHER
TRUSS HEAD TYPE AB TAPPING SCREW AND TYPE L WIDE WASHER
PAN HEAD TYPE F TAPPING SCREW AND TYPE H NARROW WASHER
HEX HEAD[2] MACHINE SCREW AND TYPE H REGULAR WASHER
HEX WASHER HEAD TYPE T TAPPING SCREW AND TYPE H WIDE WASHER
REPRESENTATIVE EXAMPLES OF CONICAL SPRING WASHER SEMS

Figure 14.43 Types of SEMs.

14.8.2 Electroplating fasteners

High-quality fasteners such as the Unbrako series of socket-head cap screws and shoulder bolts, which use the UNR thread profile, may be precision plated according to Table 14.2. Other types of fasteners also may use the plating specifications shown in Table 14.2.

(Text continued on page 922.)

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Fastening and Joining Techniques and Hardware

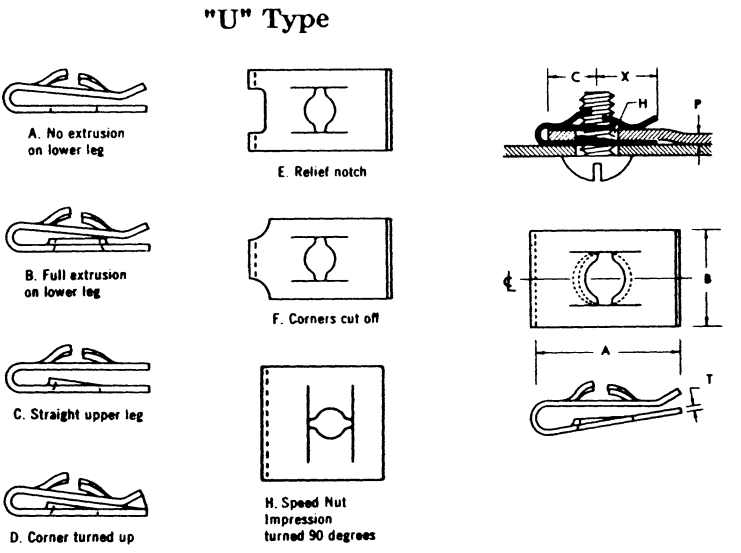

Figure 14.44 Tinnerman speed nuts.

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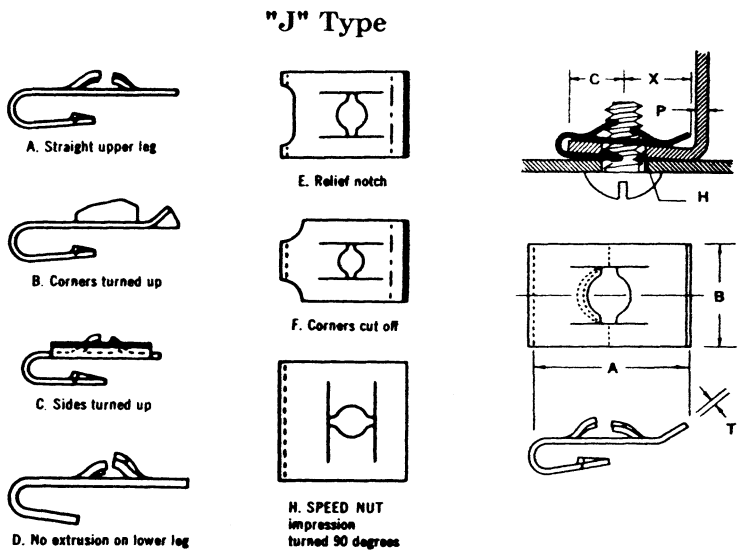

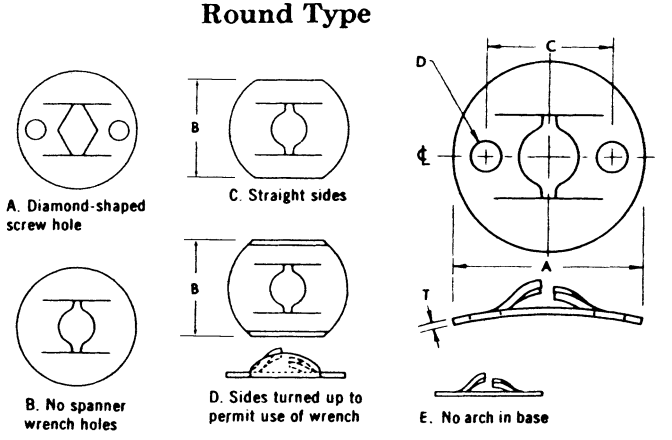

Figure 14.44 (*Continued*)

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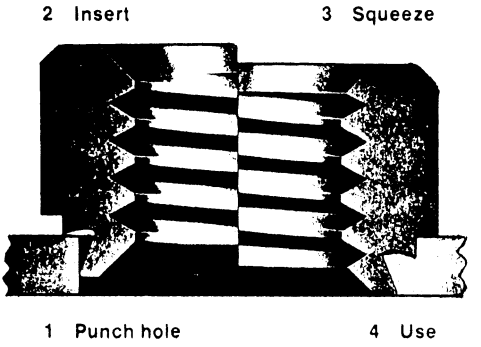

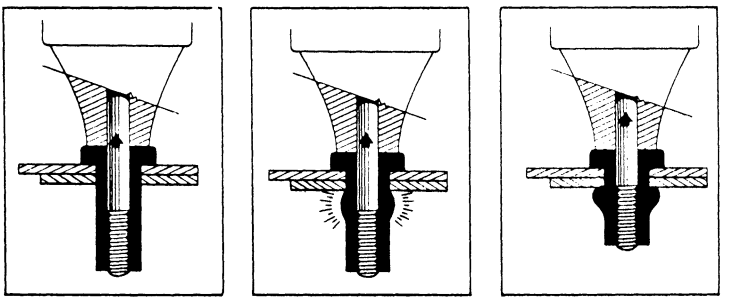

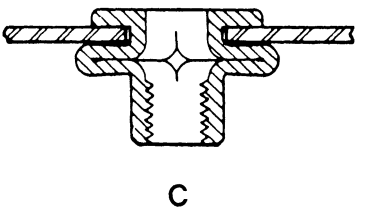

Figure 14.45 (*a*) Clinch or swage nut. (*b*) Rivnut installation. (*c*) Installed Plusnut.

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TABLE 14.2 Precision Plating Specifications for Fasteners

Type	Thickness (minimum), in			Pre- or postplate treatments or instructions	Typical specifications
	A	B	C		
Cadmium	0.0002	0.0003	0.0005	Clear postplate dip	AMS 2400 and QQ-P-416, type I
Cadmium	0.0002	0.0003	0.0005	Olive drab chromate	QQ-P-416, type II
Cadmium	0.0002	0.0003	0.0005	Iridescent dichromate	QQ-P-416, type II
Zinc	0.0002	0.0003	0.0005	Clear bright	ASTM B633, type III
Zinc	0.0002	0.0003	0.0005	Olive drab chromate	ASTM B633, type II
Zinc	0.0002	0.0003	0.0005	Iridescent dichromate	ASTM B633, type II
Zinc	0.0002	0.0003	0.0005	Supplementary phosphate	ASTM B633, type IV
Silver	0.0002	0.0003	0.0005	Nickel strike	AMS 2410, AMS 2411
Black oxide	Alloy or carbon steel	18-8 stainless			AMS 2485, Mil-C-13924
Dull nickel	0.0002	0.0003	0.0005		AMS 2403
Copper	0.0002	0.0003	0.0005		AMS 2418
Tin	0.0002	0.0003	0.0005		AMS 2408, Mil-T-10727, type I
Phosphate (class A) (Parker-Lubrite)	Dry	Nondrying oil		Manganese phosphate	AMS 2481, DOD-P-16232
Phosphate (class B) (Parkerizing)	Dry	Drying oil		Zinc phosphate	AMS 2480, DOD-P-16232
Cadmium	0.0002	0.0003	0.0005	Black dye over olive drab chromate	QQ-P-416 type II except color

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Cadmium	0.0002	0.0003	0.0005	Fluoborate bath, bake at 375° for 23 h, iridescent dichromateSilver	NAS 672 0.0002 0.0003
0.0005	Copper strike	AMS 2412			
Nickel	0.0002 NI			Thermal treat 630°	AMS 2416
Cadmium	0.0001 CD				
Vacuum cadmium	0.0002	0.0003	0.0005		Mil-C-8837, type I
Cadmium	0.0002	0.0003	0.0005	Supplementary phosphate	QQ-P-416, type III
Vacuum cadmium	0.0002	0.0003	0.0005	Iridescent dichromate "Cronak" or equivalent	Mil-C-8837, type II
Molydisulfide coating				Available with a variety of carriers, concentrations, and treatments to customer requirements	
Passivation				For austenitic series stainless steel	QQ-P-35
Passivation				For 400 series stainless steel	
Cadmium Sermetel "Metric" blue dye	0.0002	0.0003	0.0005	Clear postplate dip	AMS 2401 AMS 2506
IVD aluminum	0.0010	0.0005	0.0003	Supplementary chromate	Mil-C-83488, type II

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For more complete information on electroplating, see Chap. 13, "Plating Practices and Finishes."

14.9 Welding, Brazing, and Soldering

Welding, brazing, and soldering are all important methods of joining and fastening metals and alloys. This section will detail the various methods or processes and materials used in these three types of joining techniques.

14.9.1 Welding

Welding is a fusion process for joining metals. The heat of application causes mixing of the joint metals or of the filler metal and the joint metal. The resulting joint is as strong as the parent metal, provided the weld is made correctly.

Numerous welding methods or techniques are in common use for a vast array of applications. Modern welding methods or techniques are categorized in Fig. 14.46, which shows the process and the American Welding Society (AWS) designation. Both welding and cutting processes for metals are shown in the figure.

Although the list of processes shown in Fig. 14.46 is extensive, the majority of welding is done by the following methods:

- Stick welding (fluxed rod)—SMAW
- MIG (metal inert gas) welding—GMAW
- TIG (tungsten inert gas) welding—GTAW
- Stud arc welding—SW

Whether the welding process is gas or arc, the welder may proceed to do the weld in the *forward* or *backward* direction, as shown in Fig. 14.47. The direction of welding is left to the judgment of the welder based on the configuration of the object being welded. When the welder is looking down at the welded joint, this is normally called *in-position welding*. When the welder is looking up at the joint, this is called *out-of-position welding*. Any orientation not looking down at the weld can be considered as out-of-position welding.

Each of the various welding processes produces physical characteristics that allow the process to be identified by direct eye inspection. Figure 14.48 shows an assembly welded using the MIG process (GMAW). Here, the weld is rather rough looking and was difficult

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Welding Processes and Designations

Process	Designation
Arc welding (AW)	
Atomic-hydrogen welding	AHW
Bare-metal arc welding	BMAW
Carbon arc welding	CAW
-gas	CAW-G
-shielded	CAW-S
-twin	CAW-T
Flux-cored arc welding	FCAW
-electrogas	FCAW-EG
Gas-metal arc welding	GMAW
-electrogas	GMAW-EG
-pulsed arc	GMAW-P
-short circuiting arc	GMAW-S
Gas-tungsten arc welding	GTAW
-pulsed arc	GTAW-P
Plasma arc welding	PAW
Plasma gas-metal arc welding	PAW-GMAW
Shielded-metal arc welding	SMAW
Stud arc welding	SW
Submerged arc welding	SAW
-series	SAW-S
Solid-State Welding (SSW)	
Cold welding	CW
Diffusion welding	DFW
Explosive welding	EXW
Forge welding	FOW
Friction welding	FRW
Hot press welding	HPW
Roll welding	ROW
Ultrasonic welding	USW
Other Welding	
Electron-beam welding	EBW
Electroslag welding	ESW
Flow welding	FLOW
Induction welding	IW
Laser beam welding	LBW
Thermite welding	TW
Oxyfuel Gas Welding (OFW)	
Air acetylene welding	AAW
Oxyacetylene welding	OAW
Oxyhydrogen welding	OHW
Pressure gas welding	PGW
Resistance Welding (RW)	
Flash welding	FW
High frequency resistance welding	HFRW
Percussion welding	PEW
Projection welding	RPW
Resistance seam welding	RSEW
Resistance spot welding	RSW
Upset welding	UW

Metal Cutting Processes and Designations

Process	Designation
Thermal Oxygen Cutting (OC)	
Chemical flux cutting	FOC
Metal powder cutting	POC
Oxyfuel gas cutting	OFC
-oxyacetylene	OFC-A
-oxyhydrogen	OFC-H
-oxynatural gas	OFC-N
-oxypropane	OFC-P
Oxygen arc cutting	AOC
Oxygen lance cutting	LOC
Arc cutting (AC)	
Air-carbon arc cutting	AAC
Carbon arc cutting	CAC
Gas-metal arc cutting	GMAC
Gas-tungsten arc cutting	GTAC
Metal arc cutting	MAC
Plasma arc cutting	PAC
Shielded-metal arc cutting	SMAC
Other cutting	
Electron-beam cutting	EBC
Laser beam cutting	LBC

Recognized by The American Welding Society (AWS)

Figure 14.46 Welding processes and designations.

to clean mechanically. The welding heat setting and the diameter of the weld wire play important roles in producing a neat, clean weld that is also mechanically sound. Figure 14.49 shows the same type of joint (using the same parts) that has been welded using the TIG process (GTAW). It is immediately apparent that the TIG process is more advantageous in this application, from the point of view of both strength and cosmetic appearance. This joint is comprised of parts manufactured from AISI 304 type stainless steel. Figure 14.49 shows the welded assembly sand-blasted after welding. The TIG weld in this application was made efficiently and correctly by a skilled welder. Welding is an art as well as a science, and a good welder needs a great deal of practice and experience.

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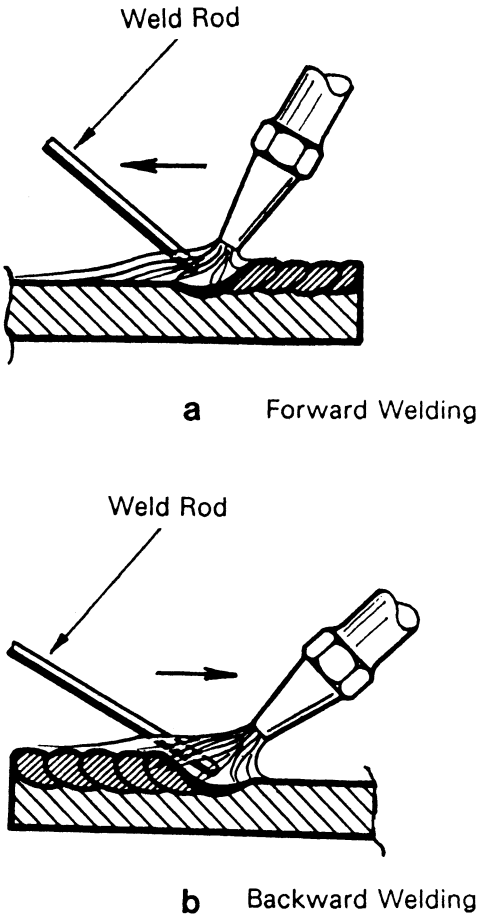

Figure 14.47 (*a*) Forward. (*b*) Backward.

In a welded assembly of numerous parts, the welder's skill and experience play an important role in producing an acceptable final weld assembly. Many welded assemblies require additional machining after the welding process because of the strains produced when the welded joints cool to room temperature. Allowance must be made in the design of such an assembly to accommodate these welding distortions, which are sometimes unavoidable.

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Figure 14.48 MIG-welded assembly.

Figure 14.49 TIG-welded assembly.

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Welding procedures and electrode sizes. The correct electrode size is one that, when used with the proper amperage and travel speed, produces a weld of the required size in the least amount of time. The electrode diameter selected for use depends largely on the thickness of the material to be welded, the position in which welding is to be performed, and the type of joint to be welded. In general, larger electrodes will be selected for applications involving thicker materials and for welding in the flat position in order to take advantage of their higher deposition rates.

For welding in the horizontal, vertical, and overhead positions, the molten weld metal tends to flow out of the joint owing to gravity. This can be controlled by using small electrodes to reduce the weld pool size. Electrode manipulation and increased travel speed along the weld joint also aid in controlling the weld pool size.

Weld groove design also must be considered when electrode size is selected. The experience of the welder often has a bearing on the size of the electrode. This is particularly true for out-of-position welding because the welder's skill determines the size of the molten pool that the welder can control.

Welds that are larger than necessary are more costly and, in certain instances, actually are harmful to the joint. Any sudden change in section size or contour of a weld, such as that caused by overwelding, creates stress concentrations. An improperly welded assembly of parts will distort on cooling, and an experienced welder can prevent this to a certain degree by applying the welds at the correct points and in the correct sequences. Tooling fixtures and weld jigs play an important role in controlling the distortion of welded assemblies when they are designed and applied properly.

Shielded-metal arc welding can be accomplished with either alternating current (ac) or direct current (dc) when the appropriate electrode is used. The melting rate of any given electrode is directly related to the electrical energy supplied to the arc via the welding controller apparatus.

Direct current (dc) always supplies a steadier arc and smoother metal transfer than alternating current (ac). Most covered electrodes operate better on reverse polarity (electrode positive), although some are suitable for and are even designed for straight-polarity welding (electrode negative). Reverse polarity produces deeper weld penetration, whereas straight polarity produces a higher electrode melting rate. Direct current is particularly suitable for thin-section welding and is preferred for vertical and overhead welding (out-of-position welding). If *arc blow* is a problem when welding with dc, change the current to ac.

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For SMAW, ac offers advantages over dc; one is the absence of arc blow, and the other is the cost of the power source for producing the weld (the welding machine or apparatus). Without arc blow, larger electrodes and higher welding currents can be used.

Welding technique. In SMAW welding, you first select the proper equipment, materials, and tools for the job. The type of welding current and its polarity then must be selected, and the power source set accordingly. The power source must be set to give the proper voltampere (VA) characteristic for the size and type of electrode being used.

Strike the arc, for the weld to begin, by tapping the end of the electrode near the beginning of the weld joint; then quickly move it to produce an arc of proper length at the beginning of the weld joint. Then move the electrode uniformly along the joint, keeping a constant arc length as the electrode melts to produce the welded joint. A good deal of practice is required, especially in out-of-position type weld joints. To break the welding arc, when the weld joint is completed, stop the forward motion of the electrode and abruptly withdraw the electrode away from the joint or move the electrode into the weld pool quickly to kill the arc and then abruptly remove the electrode, thus breaking the arc.

Note: Complete welding procedures and data for all welding processes are prepared by the American Welding Society (AWS) and are available in handbook form in its *Welding Handbook,* eighth edition, in three volumes.

Weld strength: Related equations and tables. Here we will present the equations for determining the approximate strengths of welded joints. Any equation involving a process with many variables, such as welding, can only be an approximation. With this in mind, therefore, one should allow a factor of safety when designing and calculating the strengths of welded joints.

Fillet welds. Refer to Fig. 14.50a. The basic welding equations for the fillet weld are as follows:

$$h = 0.707l$$

$$hL = \frac{P}{S_i}$$

$$A = \frac{P}{S_i}$$

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$$L = \frac{P}{S_i h}$$

where l = leg dimension of fillet weld, in
L = length of fillet weld, in
h = weld throat height, in
P = load, lb
S_i = induced stress, lb/in^2
A = throat area, in^2

Butt welds (primary). Refer to Fig. 14.50*b*. The tensile stress in a butt weld induced by a tensile load P is

$$S_t = \frac{P}{td}$$

where S_t = tensile stress, lb/in^2
P = tensile load, lb

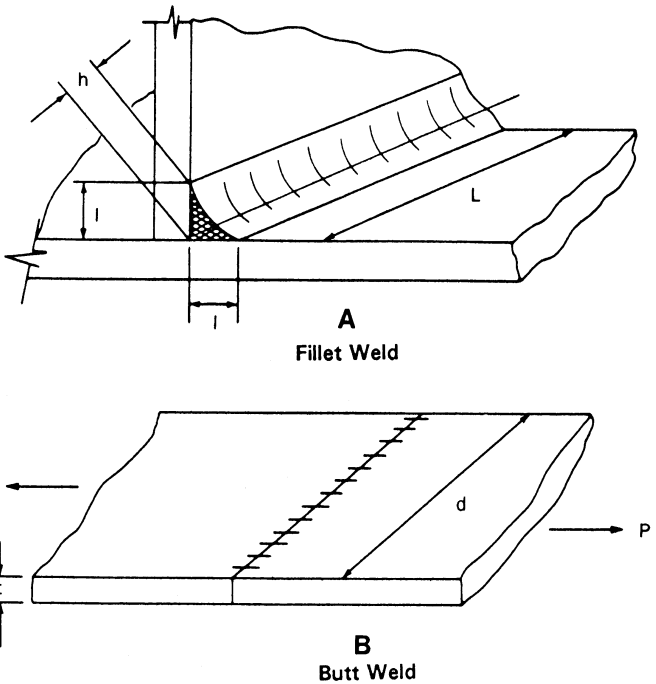

Figure 14.50 (*a*) Fillet weld. (*b*) Butt weld.

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t = material thickness, in
d = width of butt welded joint, in

For minimum leg sizes for fillet welds, see Figure 14.51*b*. For allowable design strengths and shear forces for fillet welds and partial penetration groove welds, see Fig. 14.51*a*.

Example: The allowable unit force for a fillet weld with a 0.25-in leg, using 80,000-lb/in^2 weld rod or wire, is 16,500 × 0.25 = 4125 lb/in. Thus, if the weld joint is 3 in long, the force allowable is 4125 × 3 = 12,375 lb.

Plug welds. Plug welds (Fig. 14.52) are useful in sheet metal and structural design applications. Plug welds are used primarily for shear loads, although they are not limited to this type of load. A plug weld may be subjected to a combination of shear and tensile loads. The typical sizes of plug welds are shown in Fig. 14.51c for various applications or combinations of material thicknesses. Figure 14.52 illustrates a typical plug weld.

Note: It should be noted that the weld-strength figures and tables, allowables, and examples are for *static* loads only. When the welded members are dynamically or cyclically loaded, a factor of safety should be applied. A safety factor of 3 should be applied for general dynamic conditions. In other words, if the weld joint was calculated to withstand a load of 3000 pounds force, for dynamic conditions this load should be reduced to a 1000 pounds force maximum. (Divide the calculated load by 3 to arrive at the allowable load with the factor of safety applied.)

Specifying welds. The type of welding, weld-rod strength and type, fillet or bead size, location, and length of welds all must be specified on the welding drawings of a part or assembly. Standard weld symbols recognized by the American Welding Society (AWS) should be used on the engineering drawings (see "Standard Weld Symbols" below).

Thin-section parts or any part or assembly that may pose a weld distortion problem should be reviewed in coordination with the welding department or welder prior to final design or beginning the work. Experienced welders usually know or can determine welding sequences to prevent distortion or keep it to a minimum. Welding sequence instructions may be required on the welding drawing.

Secondary machining operations usually are performed on a welded part or assembly after the welding operation to correct unavoidable distortion or dimensional changes that take place

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Design-Allowable Strengths and Shear Forces

Strength of Weld* Rod or Wire Metal, psi	Allowable Shear Stress on Throat *(h)*, psi	Allowable Unit Force, lb/Linear inches
60,000	17,000	12,500 x *l*
80,000	23,000	16,500 x *l*
100,000	29,000	21,000 x *l*
120,000	35,000	25,000 x *l*

* For intermediate weld-rod strengths, interpolation may be used. In the above table, *h = weld throat, l = length of fillet leg.*

(a)

Minimum Leg Size, (Fillet Weld)

Thickness of Thicker Plate *(t)*, inches	Minimum* Leg Size *(l)*, inches
Up to 1/4	1/8
> 1/4 to 1/2	3/16
> 1/2 to 3/4	1/4
> 3/4 to 1-1/2	5/16
> 1-1/2 to 2-1/2	3/8

*Also minimum throat *(h)* of partial penetration groove weld. Leg of weld *(l)* should not exceed thickness of thinner plate.

(b)

Plug Weld Sizes, (Diameters)

Gauge or Thickness of Thinner Member, (Inches)	Plug-Weld Hole Diameter, (Inches)
1/16 or # 16 gauge	1/4 to 3/8
3/32 or # 13 gauge	1/2
1/8 or # 11 gauge	5/8
3/16 or # 7 gauge	5/8
1/4 plate	3/4
3/8 plate	1

(c)

Figure 14.51 (*a*) Allowable shear. (*b*) Weld leg sizes. (*c*) Plug weld sizes.

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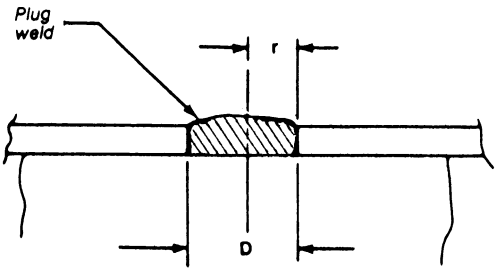
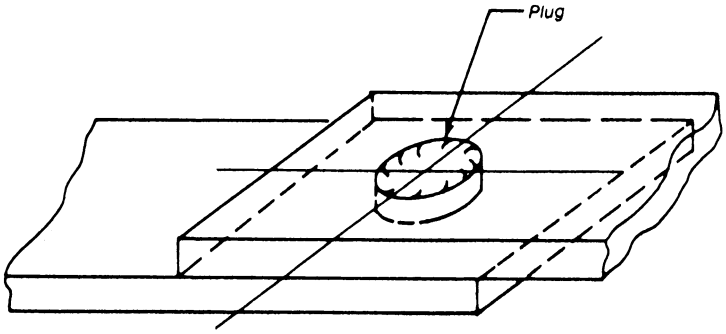


(a)



(b)

Figure 14.52 (*a*) Section of plug. (*b*) Plug-welded plates.

during welding. To reduce cost and save welding time, the amount of welding on a part or assembly should be kept to a minimum, in accordance with the strength requirements of the design or sealing requirements.

Standard weld symbols. The basic weld symbols shown in Fig. 14.53 should be used on all welding drawings, especially if the welded part is sent to an outside vendor or subcontractor. If in-house symbols are used, these should be noted on the welding drawings so that outside vendors or subcontractors know their exact meaning. The symbols shown in the figure are those recognized by the American Welding Society (AWS), the American Iron and Steel Institute (AISI), the American Society of Mechanical Engineers (ASME), the Society of Automotive Engineers (SAE), and other authorities and specification agencies.

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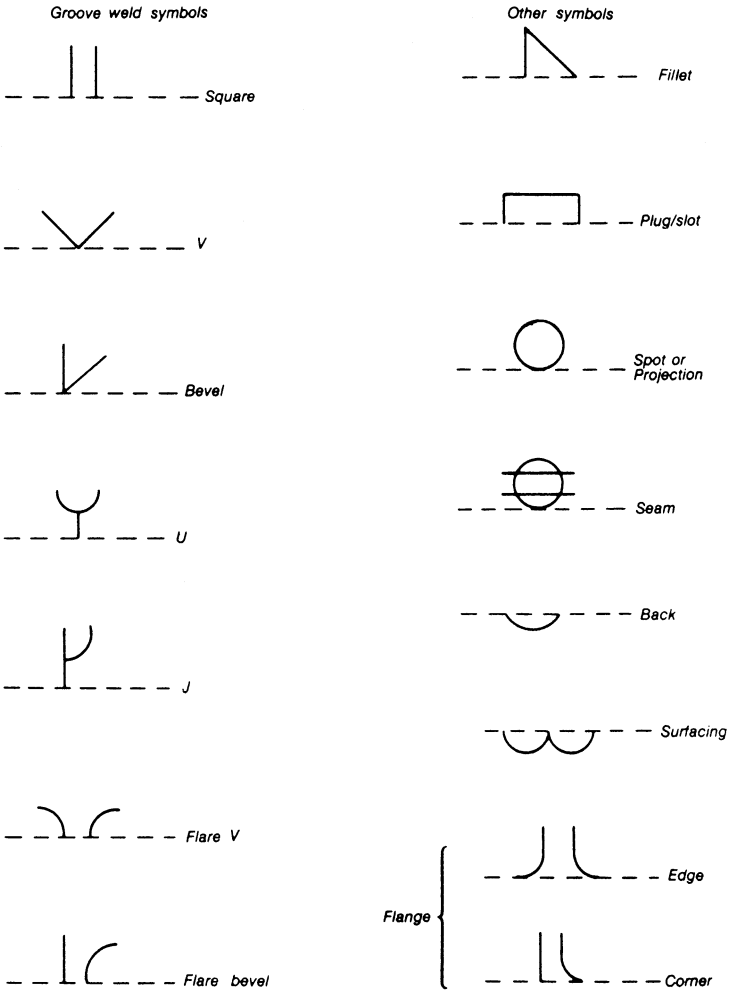

Figure 14.53 Weld symbols.

Elements of the welding symbol. When a weld is specified on an American standard engineering drawing, it should conform to certain characteristics, which are shown in Fig. 14.54. In this way, uniformity and complete understanding are maintained between the welder and the design engineer. Typical welding drawing call-outs

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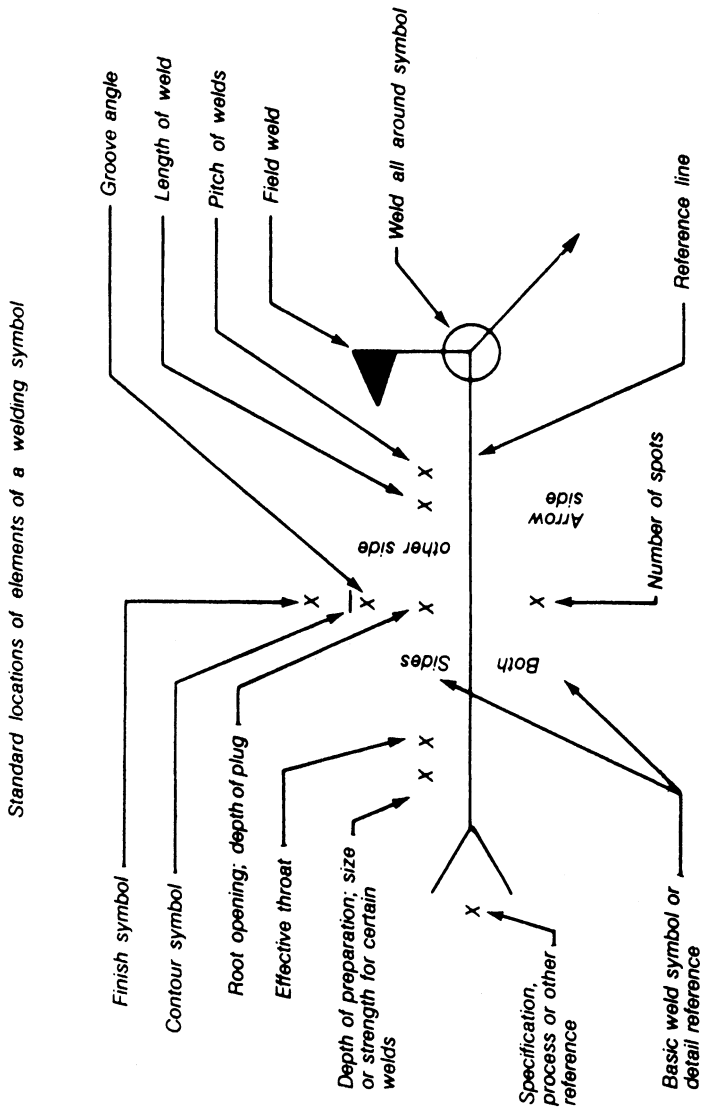

Figure 14.54 Elements of the welding symbol.

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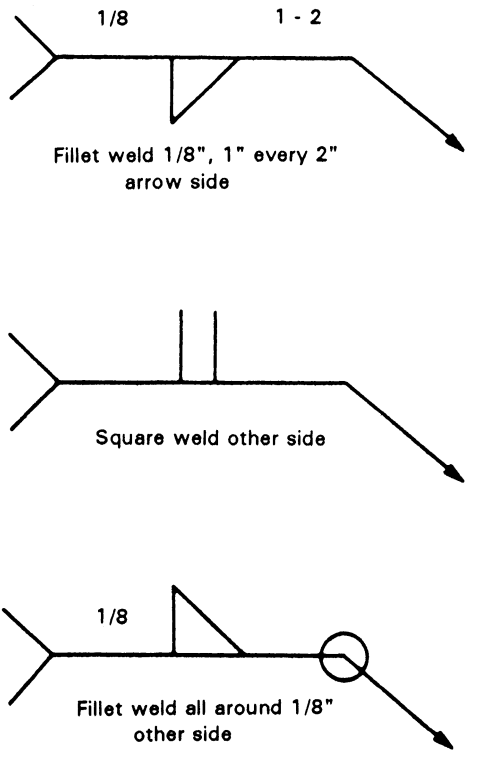

Figure 14.55 Typical weld call-outs (welding drawings).

or symbols are shown in Fig. 14.55 with an explanation of their meaning.

Types of weld joints. There are many types of weld joints or designs, and the basic ones are shown in Fig. 14.56. The various joints have been designed for different applications and strengths. Other characteristics are designed into the weld joint, such as minimal outgassing, dynamic strength, deep penetration, pressure-vessel applications, and others. Weld joints that require special preparation, such as machining, filing, or grinding, are more expensive to produce and thus are used for special applications. The majority of industrial welding consists of the simple fillet- and butt-welded joints, followed by the single-V and double-V joints.

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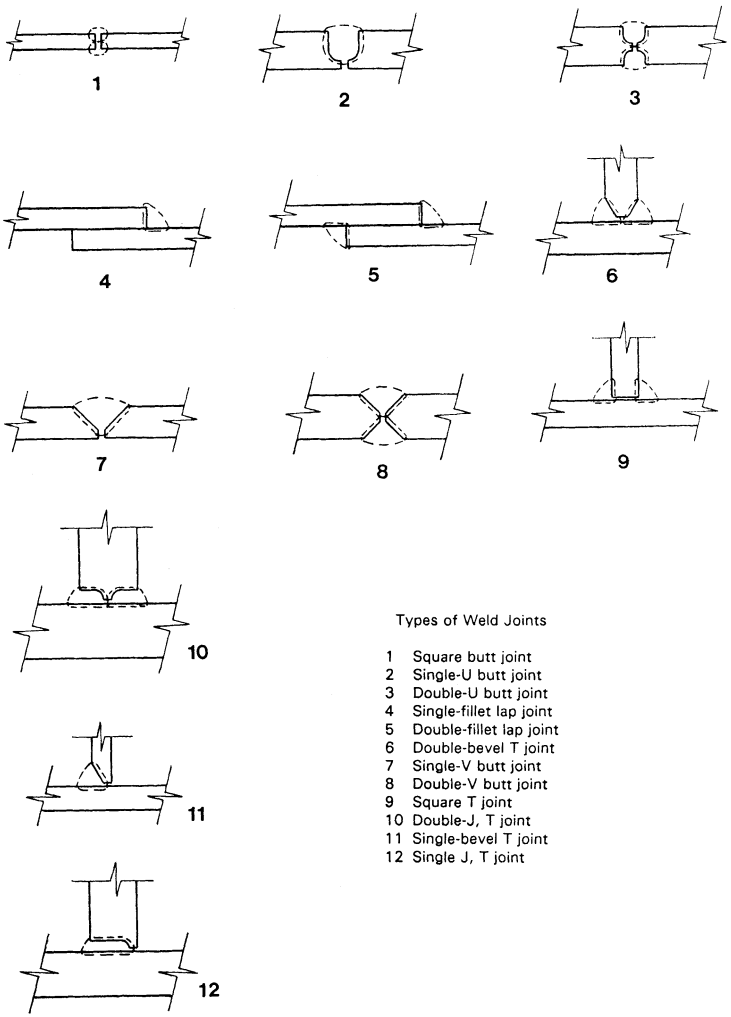

Figure 14.56 Basic weld-joint geometry.

Welding applications data. Welding is one of the most common and important means of fastening. Its applications are limitless, and the technology is constantly changing. Given here is a listing of various welding process applications that are helpful in design as well as welding work.

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Thin-gauge metal welding. Small welding flames or small arcs are required for welding thin-gauge metals. The TIG process is especially useful for producing small, accurate welds on thin materials, under 11 gauge (0.1196 in). To prevent buckling of large-area, thin materials, *heat sinks* are useful. Heat sinks may take the form of wet burlap bags or large blocks of metal clamped to the welded parts or sections. Applying *tack welds* in a specified sequence also may help to prevent buckling of large, thin sections prior to beginning the final seams.

Preheating. Large sections or masses of metal usually require a preheat stage, where the parts are heated a few hundred degrees Fahrenheit prior to beginning the welding process. This prevents thermal shock and minimizes distortion and possible cracking of the welds.

Air cooling. Welded parts or assemblies normally are allowed to cool to ambient temperature after the welding process is completed. Do not water quench welded parts immediately after welding. Because of the high temperatures generated in the welding process, cracking or distortion may occur. Changes in the grain structure of the metal may occur if the hot, welded part is cooled suddenly by water quenching.

Welding bases or platforms. A flat, level area is required for welding large assemblies. This is usually provided by structural beams embedded in the weld shop floor. The beams must be straight and leveled with a transit or leveling instrument. For smaller welded parts and assemblies, the standard welding table is used. Figure 14.57 shows a typical steel-grid welding table, which is used in many welding departments. This type of table is level and has square openings where different types of clamping and squaring tools may be attached to hold the welded assembly prior to the welding operation.

Notice the screening and plastic shielding located around the welding table area. This shielding prevents the intense ultraviolet radiation generated by the welding arc from reaching the eyes of other personnel. The intensity of the welding arc radiation is high enough to damage the membrane covering the human cornea and eyeball. It is not necessary to look directly at the welding arc for damage to occur to the eye. The arc rays can penetrate the side of the eye indirectly and cause damage. The usual effect of looking at a weld-

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Figure 14.57 A cast iron grid welding table.

ing arc is the feeling that sand has entered the eye. This usually begins to show some hours after exposure to the arc, either directly or indirectly, and is the result of scar tissue formation in the damaged eye.

Figure 14.58 shows a welder performing the TIG welding process on an aluminum electrical reactor core. This is a precision process requiring great skill by the welder. Figure 14.59 shows a welder using a pneumatic grinder to smooth the edges of a welded sheet metal assembly that was completed using the MIG process. In many companies, smoothing of the completed welds by grinding is considered part of the welding process and is performed by the welders. Small subassemblies as well as large welded assemblies are treated in this manner.

Welding stainless steels. The electrode used to weld stainless steels also should be stainless steel, matching the application. Types AISI 300 through 303 should not be welded because these are machining grades. Type AISI 304 is a preferred stainless steel for welding

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Figure 14.58 A welder welding an aluminum reactor core using the TIG process on aluminum alloy.

applications, with AISI type 304L, a special low-carbon grade for critical applications such as those used on aerospace vehicles. Too much carbon or sulfur in a stainless steel produces cracking during the welding process. AISI types 308, 309S, 310S, 316, and 316L are also suitable for welding applications because they are low in carbon content. AISI types 316 and 316L stainless steels are used widely in highly corrosive environments such as chemical and food-processing applications. The 300 series stainless steels are austenitic (nonmagnetic) and cannot be hardened by heat-treatment procedures. See Chap. 4 for more information on stainless steels.

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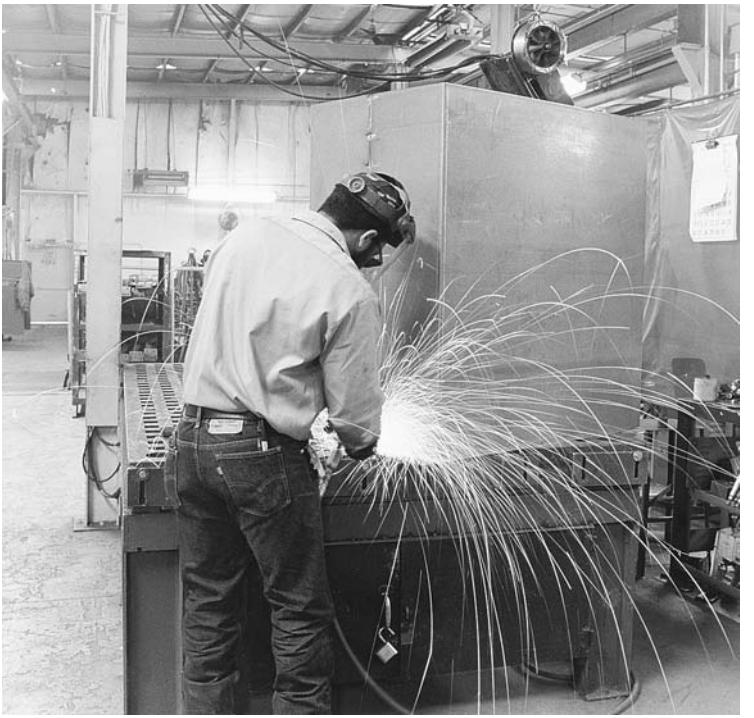

Figure 14.59 A welder grinding and smoothing the edges of a welded sheet metal assembly for an electrical power distribution product.

Welding carbon and alloy steels. The low-carbon grades from AISI 1010 through 1020 are readily weldable because they are low in carbon content. Some of the medium-carbon grades are weldable with caution, whereas the high-carbon grades are not recommended for welding (AISI 1045–1095). The higher carbon content in the steel causes cracking during the welding process. Low-alloy- and alloy-grade steels are weldable according to type and welding process employed. See Chap. 4 for more data on the low-alloy and alloy steels, including tool steels.

Cutting metals. Oxyacetylene cutting (OFC-A) is the most common welding process for cutting ferrous metals. Most ferrous metals cut cleanly using this method, except the stainless steels, high-manganese steels, and special alloy steels. To cut these difficult materials, special techniques are required wherein the molten metal can

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Figure 14.60 Laser-cut steel parts.

be blown away from the flame or arc during the cutting process. Laser beam cutting (LBC) is a modern method of cutting difficult materials and extremely thin materials. Figure 14.60 shows small parts made of carbon steel that were cut using the laser beam method. These parts are approximately 2 in long and 0.18 in thick. The quantity required did not justify building a stamping die for this part, and milling the part from stock was expensive; therefore, laser beam cutting was selected for the method of manufacture.

Many branches of industry rely on the welding processes for producing their equipment and machinery economically. Figure 14.61 shows a typical electrical power distribution industry lineup of switch gear that relies heavily on the welding processes to fasten and join the many sheet metal parts and structures required.

14.9.2 Brazing

Brazing employs a nonferrous filler metal, usually in wire or paste form, to join metal parts at a temperature above approximately 800°F but below the melting point of the base metals being joined. Various fluxes are used in the brazing process to remove oxides on

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Figure 14.61 Switch-gear equipment fabricated from sheet steel. *(Powercon Corporation, Severn, MD.)*

the base-metal parts so that the filler metal can adhere to them strongly. Sal ammoniac is a good general-purpose flux for brazing copper, phosphor-bronze, and stainless steels.

The brazing of tungsten alloys to various base metals is accomplished by pretinning the brazing surfaces of the tungsten alloy part in a nitrogen-atmosphere furnace before joining the tungsten alloy part with the base-metal part. This is done because it is extremely difficult to remove oxide layers that form on the tungsten part unless it is pretinned and protected from the atmosphere. Many of the various designs of electrical contact points are brazed to their base-metal mountings, although riveting is sometimes employed.

Brazing heat. Heat for brazing parts may be supplied by the following methods:

- Torch brazing
- Furnace brazing
- Resistance brazing

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- Dip brazing
- Vacuum-furnace brazing
- Induction brazing

When there is an unusual condition in the brazing method or process, a brazing specialist should be consulted. So many brazing materials and fluxes are available that only an expert in the field may be able to solve your particular brazing problem.

In the normal brazing process, a suitable brazing wire or paste is selected, and the parts to be brazed are set up or clamped into position (brazing fixtures sometimes are employed) after the joint has been fluxed with the proper flux for the application. Heat is applied to the parts to be joined, and when they are hot enough, the filler wire is fed into the brazed joint, where a wetting action takes place, and the joint is filled with the melted brazing filler. The joint is then allowed to air cool to room temperature. The method of fluxing and applying the filler metal is critical for a well-brazed joint. It requires considerable skill and practice to braze a difficult joint or complicated setup. Excess brazing filler should not be used on any brazed joint because it wastes material and produces an inefficient joint.

Brazing pastes and alloys. Brazing and soldering alloys are available as wire, strip, preformed shapes, and pastes. Brazing pastes are applied to the joint prior to heating and therefore are applicable for manual as well as automated processing. Flux is also compounded in some of the brazing pastes, making their use easily applicable to production operations.

Lucas-Milhaupt (Handy and Harman Company) produces an extensive array of pastes for soldering and brazing in their HandyFlo series 110, 120, 210, 310, 320, and 330, which are listed in Fig. 14.62. Other standard Handy and Harman brazing materials are outlined in Fig. 14.63. With some of the new brazing products, it is now possible to join ceramics, diamonds, and other difficult to wet materials.

14.9.3 Soldering

The use of lead or tin base alloys having melting points below 800°F for joining metal parts is known as *soft soldering.* Such joints usually do not have great mechanical strength, although they may be required to carry electric currents.

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	110	120	210	310	320	330
HEATING METHODS						
Torch	•	•	•			
Induction	•	•	•			
Resistance	•	•	•			
Vacuum Brazing				•	•	•
Atmospheric Furnace	•	•	•	•	•	•
Infrared, Hot plate						
Oven						
TEMPERATURE RANGE						
300 - 500° F 149-260° C						
500 - 1000° F 260-524° C						•
1000 - 1500° F 524-815° C	•	•		•	•	•
1500 - 2000° F 815-1093° C			•	•	•	•
Includes Flux	•	•	•			
Can Be Boron Modified	•	•	•			
MATERIALS JOINED						
Copper	•	•	•	•	•	•
Brass	•	•		•	•	
Cold rolled steels	•	•	•	•	•	•
Stainless Steel	•	•	•	•	•	•
Non-ferrous alloys	•	•	•	•	•	•
Tungsten Carbide	•	•	•			

Figure 14.62 Brazing paste properties.

The three basic standard soldering alloys are

- 60% tin, 40% lead—melting point 375°F
- 50% tin, 50% lead—melting point 420°F
- 40% tin, 60% lead—melting point 460°F

A number of other alloys are available. The standard 60-40 solder is useful for most electrical/electronic soldering, and a small amount of antimony may be added for improving quality and strength. The electronic wire solders are usually made with a rosin flux core. The flux is noncorrosive and nonconducting and may be removed after the soldering operation with naphtha, Varsol, or enamel paint thinners. Rosin-cored solders can be stored for extensive periods without degradation of the rosin flux core.

Preforms are also produced in soldering alloys. A *preform* is a stamped shape, made of solder alloy, that will fit a particular device or application. Some of the delicate soldering operations would be difficult or impossible without preforms.

Figure 14.64 shows a typical printed circuit board that had been soldered automatically in a "wave" soldering operation. This board

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H & H Alloy Designations	AWS A 5.8	AMS Spec.	Federal Spec. QQ-B-654A	Solidus °F	Solidus °C	Liquidus °F	Liquidus °C	Nominal Compositions % Ag	Cu	Zn	Others	Comments
Easy-Flo 45	BAg-1	4769B	VII	1125	605	1145	620	45	15	16	24Cd	Versatile alloy; for Fe&Ni base alloys
Easy-Flo	BAg-1a	4770F	IV	1160	625	1175	635	50	15.5	16.5	18Cd	For ferrous, non-ferrous, dissimilar metals.
Easy-Flo 35	BAg-2	4768D	VIII	1125	605	1295	700	35	26	21	18Cd	Gen. purpose for larger gaps.
Easy-Flo 30	BAg-2a			1125	605	1310	710	30	27	23	20Cd	For ferrous, non-ferrous, dissimilar metals.
Easy-Flo 3	BAg-3	4771D	V	1170	630	1270	690	50	15.5	15.5	16Cd/3Ni	For tungsten carbide brazing. Al-Bronze to steel. Stainless Steels.
Sil-Fos 5	BCuP-3			1190	643	1495	812	5	89		6P	Same as Sil-Fos.
Sil-Fos	BCuP-5		BCuP-5	1190	643	1475	801	15	80		5P	For Cu or Cu alloys — Not for Fe Alloys.
Sil-Fos 6	BCuP-4			1190	643	1325	718	6.0	86.5		7.5P	
Sil-Fos 18				1191	643	1191	643	17.75	75		7.25P	
69-014				1215	657	1270	687		86.7		6.3P/7Sn	
70-873				1245	674	1285	696		87.3		7.1P/5.6Sn	
Fos-Flo 7	BCuP-2			1310	709	1460	793		92.75		7.25P	Low cost alloy for copper & copper alloys.
Fos-Flo 8				1350	732	1350	732		91.5		8.5P	
Braze 300	BAg-20		BAg-20	1250	675	1410	765	30	38	32		For steel & non-ferrous alloys melting above 1450°F; Ni-Ag knife handle
Braze 380	BAg-34			1200	650	1330	720	38	32	28	2 Sn	Cd free. For small gaps, Fe, Cu alloys.
Braze 403	BAg-4		BAg-4	1220	660	1435	780	40	30	28	2Ni	For tungsten carbides — stainless food handling equip. (no Cd).
Braze 404				1220	660	1580	860	40	30	25	5Ni	Brazing carbides & stainless steels.
Braze 450	BAg-5		BAg-5	1225	665	1370	745	45	30	25		For band instruments (Cu alloys), brass lamps.
Braze 495	BAg-22			1260	680	1290	700	49	16	23	7.5Mn/4.5Ni	For brazing of carbides and stainless steel.
Braze 505	BAg-24			1220	660	1305	705	50	20	28	2Ni	For Ni & Fe base alloys — retards interface corrosion (no Cd).
Braze 541	BAg-13	4772E		1340	725	1575	855	54	40	5	1Ni	For stainless steels used at elevated temps.
Braze 559	BAg-13a	4765A	BAg-13a	1420	770	1640	895	56	42		2Ni	Atmosphere brazing for high temp (NoZn).
Braze 560	BAg-7		BAg-7	1145	620	1205	650	56	22	17	5Sn	Food handling equipment (Cd free).
Braze 600				1245	675	1325	720	60	25	15		For Monel & other nickel alloys.
Braze 603	BAg-18	4773B	BAg-18	1115	600	1325	720	60	30		10Sn	Low temp. seals on vacuum parts.
Braze 630	BAg-21	4774B		1275	690	1475	800	63	28.5		6Sn/2.5Ni	Stainless steel food equip./400 stainless.
Braze 650	BAg-9		BAg-9	1240	670	1325	720	65	20	15		For silverware, Fe and Ni alloys.
Braze 720	BAg-8			1435	780	1435	780	72	28			Electronics where Cd & Zn not tolerated.
Hi-Temp 095	4764B			1615	880	1770	925		52.5		38Mn, 9.5Ni	High strength for carbides, steels.
Hi-Temp 870				1760	960	1885	1030		87		10Mn, 3 Co	High temperature strength for carbides, tool steel, stainless and nickel alloys.
Premabraze 616	BVAg-29			1155	625	1305	705	61.5	24		14.5 In	For ferrous, non-ferrous in vacuum.
Premabraze 130	BAu4	4787B		1742	950	1742	950				82 Au, 18 Ni	Oxidation resistant to 1500°F, service.

Figure 14.63 Standard brazing materials.

was taken from a piece of automotive equipment that failed in service. All the copper foil lines on the printed circuit board are covered with solder, with the termination points neatly made.

Soldering aluminum. Aluminum soldering employs a soldering alloy of 60 to 75 percent tin, the remainder being zinc. Special aluminum fluxes are available, and the process is carried out at a temperature of 550 to 775°F.

Commercial and high-purity aluminums are easiest to solder, with wrought alloys that contain no more than 1 percent magnesium or manganese the next easiest. The heat-treatable alloys are more difficult. Forged and cast aluminum alloys are not recommended for soldering, although it may be possible to a limited extent. The low-temperature brazing alloys may do the job more efficiently, with a higher-strength joint possible.

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Figure 14.64 An electrically damaged PC board with solder-coated foil.

Ultrasonic soldering. The following metals and alloys may be soldered ultrasonically: aluminum, brass, copper, germanium, magnesium, silicon, and silver.

14.10 Adhesive Bonding

Adhesive bonding is used very frequently in modern manufacturing operations. The methods generally are fast, strong, and economical when used in the proper manner on appropriate articles. Entire fuselage sections are bonded or cemented on modern aircraft to

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replace riveting. The method not only affords lighter weight but also is stronger and requires no maintenance. The bonding strength of cyanoacrylate adhesives is on the order of thousands of pounds of tension for 1 in^2 of bonded surface area.

Structural adhesives. Following is a list of the various types of adhesives used in industrial applications:

- Hot-melt adhesives, thermoplastic resins—l00 percent solids
- Dispersion or solution adhesives, thermoplastic resins—20 to 50 percent solids
- Silicone adhesives, thermoset—l00 percent solids (rubber-like with high impact and peel strengths)
- Anaerobic adhesives, thermoset—100 percent solids, liquid (thread-locking uses such as Loctite series adhesives)
- Phenolic or urea adhesives, thermoset resins—l00 percent solids or solution
- Epoxy adhesives, thermoset—100 percent solids, liquid
- Polyurethane adhesives, thermoset—100 percent solids, liquid
- Cyanoacrylate adhesives, thermoset—100 percent solids, liquid (hazard of bonding skin on contact; almost instant set; 30-second to 5-minute cure; high strength)
- Modified acrylic adhesives, thermoset—100 percent solids, liquid, or paste (fast cure, 3 to 60 seconds)

Weldbonding. A combination of spot welding and adhesive bonding, this process is used on aerospace assemblies to cut costs, reduce weight, and increase strength. The method affords lighter weight than riveting, is stronger, yields air- and fuel-tight joints, and produces a smooth exterior surface that reduces wind resistance. The structural adhesives are applied prior to the spot-welding operation, and then the bonded and welded assembly is oven cured at an elevated temperature for a predetermined time interval.

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Chapter

15

Safety Practices in Industry

The metalworking industries in the United States and throughout the world perform their functions and manufacturing practices under a variety of conditions, some of which are hazardous and may pose health problems to metalworkers. In order to protect the people involved in all classes of industrial manufacturing processes and situations, the Occupational Safety and Health Administration (OSHA) was created by the United States government.

OSHA is responsible for generating and administering the rules and regulations that were designed to protect American workers from industrial and manufacturing practices and materials that have proven to be safety and health hazards. For example, for many years, workers handled and processed asbestos without the slightest idea or knowledge that this material was dangerous to their health and in many instances caused fatal health problems. Likewise, processes for mercury and cadmium metals can pose serious health and environmental problems, as can the indiscriminate handling and disposal of toxic waste products.

In order to help protect the environment, the Environmental Protection Agency (EPA) was established. This agency generates and administers the rules and regulations designed to help protect the environment from poisonous and otherwise harmful chemicals and materials used throughout industry. It should be noted that many of the heavy metals and their compounds are toxic. Many

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organic, carbon-based materials and chemicals also are toxic, some to an extreme extent. Many materials and compounds are also nonbiodegradable, which means that they will remain in the environment indefinitely as waste products.

Bearing the preceding in mind, we can readily see why these regulating agencies and administrations are necessary in the modern industrial world. Section 15.1.2 is a reference listing of the OSHA standards for use in any of the categories currently under regulation. The standard you are interested in checking may be obtained directly from OSHA or your company risk manager. All manufacturing installations are required to keep the OSHA and EPA regulating standards on their premises and make them available to any employee interested in obtaining information from these regulatory standards.

If you have doubts about the possible hazards of the materials, substances, and processes you use or come into contact with during your job duties, check the applicable OSHA or EPA standards. Modern American industrial employees are no longer required to forfeit their health or lives because of their job requirements, which may be in violation of the OSHA and EPA regulatory standards.

15.1 Typical Industrial Hazards

The following list of safety and health hazards is only a minute example of the conditions, materials, and substances that a metalworking employee could be subjected to:

- Welding over cadmium-plated parts (highly toxic fumes from the cadmium)
- Case-hardening steel parts with cyanide compounds without proper ventilation and equipment
- Fumes from electroplating processes
- Grinding and machining beryllium alloys (beryllium-copper, beryllium-nickel)
- Machining and grinding magnesium
- Machining plastics with fiberglass fillers without ventilation and evacuation equipment
- Skin contact with plating solutions
- Fumes from metal etching processes

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- Foot and hand injuries when handling large sheet metal parts
- Injuries on machine tools not equipped with guards and shields
- Injuries on stamping dies owing to inadequate or missing shields
- Ultraviolet radiation burns and eye injuries from welding processes
- Paint fumes in undesignated painting areas

15.1.1 Safety practices when operating machine tools

Many grave injuries occur in the operation of machine tools, especially during manual operation. The following list of precautions will help to prevent injury to machine tool operators, machinists, and tool and die makers:

- Wear the proper eye protection.
- Know exactly what to expect your machine to do *before* you turn on the power switch.
- Do not wear neckties or any loose clothing while operating a machine tool; the sleeves of long-sleeve shirts also must be rolled up past the elbow.
- Do not wear rings, watches, neck chains, or wrist bracelets while operating machine tools.
- Do not wear gloves while operating machine tools.
- Know instinctively where the power switch is located on your machine tool so that it may be switched off quickly in an emergency.
- Keep your work area clear of obstructions.

15.1.2 OSHA standards by category

See Fig. 15.1.

15.2 Product Liability

Safety in product design should be of prime importance to all product designers. There have been over 500 awards of more than $1

(Text continued on page 955.)

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Safety Practices in Industry

PART 1910

OCCUPATIONAL SAFETY AND HEALTH STANDARDS

SUBPART A—GENERAL

1910.1 Purpose and scope.
1910.2 Definitions.
1910.3 Petitions for the issuance, amendment, or repeal of a standard.
1910.4 Amendments to this part.
1910.5 Applicability of standards.
1910.6 Incorporation by reference.
1910.7 Definition and requirements for a nationally recognized testing laboratory.

SUBPART B—ADOPTION AND EXTENSION OF ESTABLISHED FEDERAL STANDARDS

1910.11 Scope and purpose.
1910.12 Construction work.
1910.13 Ship repairing.
1910.14 Shipbuilding.
1910.15 Shipbreaking.
1910.16 Longshoring.
1910.17 Effective dates.
1910.18 Changes in established Federal standards.
1910.19 Special provisions for air contaminants.

SUBPART C—GENERAL SAFETY AND HEALTH PROVISIONS

1910.20 Access to employee exposure and medical records.

SUBPART D—WALKING—WORKING SURFACES

1910.21 Definitions.
1910.22 General requirements.
1910.23 Guarding floor and wall openings and holes.
1910.24 Fixed industrial stairs.
1910.25 Portable wood ladders.
1910.26 Portable metal ladders.
1910.27 Fixed ladders.
1910.28 Safety requirements for scaffolding.
1910.29 Manually propelled mobile ladder stands and scaffolds (towers).
1910.30 Other working surfaces.
1910.31 Sources of standards.
1910.32 Standards organizations.

SUBPART E—MEANS OF EGRESS

1910.35 Definitions.
1910.36 General requirements.
1910.37 Means of egress, general.
1910.38 Specific means of egress requirements by occupancy.
[Reserved]

Figure 15.1 Table of OSHA standards.

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Safety Practices in Industry

1910.39 Sources of standards.
1910.40 Standards organizations.

SUBPART F—POWERED PLATFORMS, MANLIFTS AND VEHICLE-MOUNTED WORK PLATFORMS

1910.66 Power platforms for building maintenance.
1910.67 Vehicle-mounted elevating and rotating work platforms.
1910.68 Manlifts.
1910.69 Sources of standards.
1910.70 Standards organizations.

SUBPART G—OCCUPATIONAL HEALTH AND ENVIRONMENTAL CONTROL

1910.94 Ventilation.
1910.95 Occupational noise exposure.
1910.96 Ionizing radiation.
1910.97 Nonionizing radiation.
1910.98 Additional delay in effective date.
1910.99 Sources of standards.
1910.100 Standards organizations.

SUBPART H—HAZARDOUS MATERIALS

1910.101 Compressed gases (general requirements).
1910.102 Acetylene.
1910.103 Hydrogen.
1910.104 Oxygen.
1910.105 Nitrous oxide.
1910.106 Flammable and combustible liquids.
1910.107 Spray finishing using flammable and combustible materials.
1910.108 Dip tanks containing flammable or combustible liquids.
1910.109 Explosives and blasting agents.
1910.110 Storage and handling of liquified petroleum gases.
1910.111 Storage and handling of anhydrous ammonia.
1910.112 [Reserved]
1910.113 [Reserved]
1910.114 Effective dates.
1910.115 Sources of standards.
1910.116 Standards organizations.
1910.120 Hazardous Waste Operations and Emergency Response

SUBPART I—PERSONAL PROTECTIVE EQUIPMENT

1910.132 General requirements.
1910.133 Eye and face protection.
1910.134 Respiratory protection.
1910.135 Occupational head protection.
1910.136 Occupational foot protection.
1910.137 Electrical protective devices.
1910.138 Effective dates.
1910.139 Sources of standards.
1910.140 Standards organizations.

Figure 15.1 (*Continued*)

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SUBPART J—GENERAL ENVIRONMENTAL CONTROLS

1910.141 Sanitation.
1910.142 Temporary labor camps.
1910.143 Nonwater carriage disposal systems.
1910.144 Safety color code for marking physical hazards.
1910.145 Specificatons for accident prevention signs and tags.
1910.146 [Reserved]
1910.147 Sources of standards.
1910.148 Standards organizations.
1910.149 Effective dates.

SUBPART K—MEDICAL AND FIRST AID

1910.151 Medical services and first aid.
1910.152 [Reserved]
1910.153 Sources of standards.

SUBPART L—FIRE PROTECTION

1910.155 Scope, application and definitions applicable to this part.
1910.156 Fire brigades.

PORTABLE FIRE SUPPRESSION EQUIPMENT

1910.157 Portable fire extinguishers.
1910.158 Standpipe and hose systems.

FIXED FIRE SUPPRESSION EQUIPMENT

1910.159 Automatic sprinkler systems
1910.160 Fixed extinguishing systems, general.
1910.161 Fixed extinguishing systems, dry chemical.
1910.162 Fixed extinguishing systems, gaseous agent.
1910.163 Fixed extinguishing systems, water, spray and foam.

OTHER FIRE PROTECTION SYSTEMS

1910.164 Fire detection systems
1910.165 Employee alarm systems
Appendices A–E

SUBPART M—COMPRESSED GAS AND COMPRESSED AIR EQUIPMENT

1910.166 Reserved
1910.167 Reserved
1910.168 Reserved

1910.169 Air receivers.
1910.170 Sources of standards.
1910.171 Standards organizations.

SUBPART N—MATERIALS HANDLING AND STORAGE

1910.176 Handling materials—general.
1910.177 Servicing multi-piece and single piece rim wheels.
1910.178 Powered industrial trucks.

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Figure 15.1 (*Continued*)

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Safety Practices in Industry

1910.179 Overhead and gantry cranes.
1910.180 Crawler, locomotive, and truck cranes.
1910.181 Derricks.
1910.182 Effective dates.
1910.183 Helicopters.
1910.184 Slings.
1910.189 Sources of standards.
1910.190 Standards organizations.

SUBPART O—MACHINERY AND MACHINE GUARDING

1910.211 Definitions.
1910.212 General requirements for all machines.
1910.213 Woodworking machinery requirements.
1910.214 Cooperage machinery.
1910.215 Abrasive wheel machinery.
1910.216 Mills and calenders in the rubber and plastics industries.
1910.217 Mechanical power presses.
1910.218 Forging machines.
1910.219 Mechanical power-transmission apparatus.
1910.220 Effective dates.
1910.221 Sources of standards.
1910.222 Standards organizations.

SUBPART P—HAND AND PORTABLE POWERED TOOLS AND OTHER HAND-HELD EQUIPMENT

1910.241 Definitions.
1910.242 Hand and portable powered tools and equipment, general.
1910.243 Guarding of portable powered tools.
1910.244 Other portable tools and equipment.
1910.245 Effective dates.
1910.246 Sources of standards.
1910.247 Standards organizations.

SUBPART Q—WELDING, CUTTING AND BRAZING

1910.251 Definitions.
1910.252 General requirements.
1910.253 Oxygen-fuel gas welding and cutting.
1910.254 Arc welding and cutting.
1910.255 Resistance welding.
1910.256 Sources of standards.
1910.257 Standards organizations.

SUBPART R—SPECIAL INDUSTRIES

1910.261 Pulp, paper, and paperboard mills.
1910.262 Textiles.
1910.263 Bakery equipment.
1910.264 Laundry machinery and operations.
1910.265 Sawmills.
1910.266 Pulpwood logging.
1910.267 Agricultural operations.
1910.268 Telecommunications.
1910.272 Grain handling facilities.
1910.274 Sources of standards.
1910.275 Standards organizations.

SUBPART S—ELECTRICAL

1910.301 Introduction
1910.302 Electric utilization systems

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Figure 15.1 (*Continued*)

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Safety Practices in Industry

1910.303 General requirements
1910.304 Wiring design and protection
1910.305 Wiring methods, components, and equipment for general use
1910.306 Specific purpose equipment and installations
1910.307 Hazardous (classified) locations
1910.308 Special systems
1910.309
1910.330 [Reserved] Safety-Related Work practices
1910.331
360 [Reserved] Safety-Related Maintenance Requirements
1910.361
380 [Reserved] Safety Requirements for Special Equipment
1910.381
398 [Reserved] Definitions
1910.399 Definitions applicable to this subpart
Appendices A–C

Subpart T—Commercial Diving Operations

1910.401 Scope and application.
1910.401 Definitions.
1910.410 Qualifications of dive team.
1910.411 Medical requirements.
1910.420 Safe practice manual.
1910.421 Pre-dive procedures.
1910.422 Procedures during dive.
1910.423 Post-dive procedures.
1910.424 SCUBA diving
1910.425 Surface-supplied air diving.
1910.426 Mixed-gas diving.
1910.427 Liveboating.
1910.430 Equipment.
1910.440 Recordkeeping requirements.
1910.441 Effective date.
Appendix A
Subpart U–Y [Reserved]

SUBPART Z—TOXIC AND HAZARDOUS SUBSTANCES

1910.1000 Air Contaminants.
1910.1001 Asbestos tremolite, anthophyllite, and actinolite
1910.1002 Coal tar pitch volatiles; interpretation of term.
1910.1003 4-Nitrobiphenyl.
1910.1004 alpha-Naphthylamine.
1910.1005 4, 4'-Methylene bis(2-chloroaniline).
1910.1006 Methyl chloromethyl ether
1910.1007 3, 3'-Dichlorobenzine (and its salts)
1910.1008 bis-Chloromethyl ether.
1910.1009 beta-Naphthylamine.
1910.1010 Benzidine.
1910.1011 4-Aminodiphenyl.
1910.1012 Ethyleneimine.
1910.1013 beta-Propiolactone.
1910.1014 2-Acetylaminofluorene.
1910.1015 4-Dimethylaminoazobenzine.

Figure 15.1 (*Continued*)

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Safety Practices in Industry

1910.1016	N-Nitrosodimethylamine.
1910.1017	Vinyl Chloride.
1910.1018	Inorganic arsenic.
1910.1025	Lead.
1910.1028	Benzene.
1910.1029	Coke Oven Emissions
1910.1043	Cotton dust.
1910.1044	1,2 - dibromo - 3 - chloropropane.
1910.1045	Acrylonitrile.
1910.1047	Ethylene Oxide
1910.1048	Formaldehyde
1910.1011	Asbestos
1910.1200	Hazard communication.
1910.1450	Occupational Exposure to Hazardous Chemicals in Laboratories.

AUTHORITY: The provisions of this Part 1910 issued under secs. 6(a), 8(g), 84 Stat. 1593, 1598; 29 U.S.C. 655, 657.

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Figure 15.1 (*Continued*)

million granted in the United States since 1962 arising from product liability lawsuits brought against manufacturers. It is of prime importance for a product designer or design group never to sacrifice safety for profit. Some of the criteria to consider and make note of during the design stages of a product are

1. All possible hazards in using or misusing the product
2. The environment in which the product is used
3. The typical user of the product and the typical nonuser
4. All instructions and warnings that are to be presented with the product

Nearly all products can be dangerous to one degree or another if misapplied. This leaves the product designer with much to consider when designing a product. Some of the strongest safeguards available to designers and manufacturers against product liability lawsuits are

1. The use of prototypes and fully functional models to demonstrate a product's characteristics. Also important are quality-control tests of random-production-run samples of the product.
2. Accurate records of qualitative test results, including high-speed film records and laboratory test equipment readings.

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3. The application of warning labels and the supplying of accurate instructions with the product in the form of instruction books and product brochures. Warning labels must attract the attention of the user, be clear and understandable, and finally, convey the nature and extent of the probable harm resulting from misuse or failure to follow the warnings and instructions issued with the product.

Following these safeguards, the product designer and manufacturer will be in a strong position if a product liability lawsuit is brought against the manufacturer in relation to one of its products.

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Chapter

16

Societies, Associations, Institutes, and Specification Authorities

Following is a listing of recognized specification authorities, societies, and institutes from which the design engineer can obtain specifications and standards covering many areas of engineering design and manufacturing.

Many of the standards are revised periodically by these authorities to keep pace with changing technology. It is therefore suggested that copies of the American standards you require to perform your job function be obtained directly from the standards organizations that generate them. In this way, you are assured of using the most recent standard and its revisions. Updates to the standards listings are distributed periodically to those on the organization mailing lists, or annual standards listing manuals may be ordered directly from the standards organizations.

Many of the standards organizations publish handbooks and manuals related to their particular fields that are technically excellent. Indexes to the standards are also available for pinpointing your area of interest in the form of annual standards catalogs.

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16.1 Standards Organizations and Their Acronyms

AAR—Association of American Railroads
Washington, DC 20001-1564
www.aar.org

ACA—American Chain Association
Naples, FL 34109
www.americanchainassn.org

ABMA—American Bearing Manufacturers Association
Washington, DC 20036
www.abma-dc.org

AGMA—American Gear Manufacturers Association
Alexandria, VA 22314-1581
www.agma.org

AIA—Aerospace Industries Association
Arlington, VA 22209-3901
www.aia-aerospace.org

AISC—American Institute of Steel Construction
Chicago, IL 60601-2001
www.aisc.org

AISI—American Iron and Steel Institute
Washington, DC 20036
www.steel.org

The Aluminum Association
Washington, DC 20006
www.aluminum.org

ANSI—American National Standards Institute, Inc.
Washington, DC 20036
www.ansi.org

API—American Petroleum Institute
Washington, DC 20005-4070
www.api.org

ASM International—American Society for Materials International
Materials Park, OH 44073-0002
www.asminternational.org

ASME—American Society of Mechanical Engineers
New York, NY 10016-5990
www.asme.org

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Societies, Associations, Institutes, and Specification Authorities 959

ASTLE—American Society of Tribologists and
Lubrication Engineers
Park Ridge, IL 60068
www.stle.org

ASTM International—American Society for Testing and Materials
West Conshohocken, PA 19428-2959
www.astm.org

AWS—American Welding Society
Miami, FL 33126
www.aws.org

BSA—Bearing Specialists Association
Glen Ellyn, IL 60137
www.bsahome.org

CDA—Copper Development Association, Inc.
New York, NY 10016
www.copper.org

EEI—Edison Electric Institute
Washington, DC 20004-2696
www.eei.org

FEMA—Farm Equipment Manufacturers Association
St. Louis, MO 63141-6369
www.farmequip.org

IEEE—Institute of Electrical and Electronics Engineers
New York, NY 10016-5997
www.ieee.org

IFI—Industrial Fasteners Institute
Cleveland, OH 44114
www.industrial-fasteners.org

IIE—Institute of Industrial Engineers
Atlanta, Norcross, GA 30092
www.iienet.org

ISA—Instrument Society of America
Research Triangle Park, NC 27709
www.isa.org

MPIF—Metal Powder Industries Federation
Princeton, NJ 08540
www.mpif.org

MPTA—Mechanical Power Transmission Association
Naples, FL 34109
www.mpta.org

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NEMA—National Electrical Manufacturers Association
Rosslyn, VA 22209
www.nema.org

NFFS—Non-Ferrous Founder's Society
Park Ridge, IL 60068
www.nffs.org

NFPA—National Fire Protection Association
(National Electrical Code)
Quincy, MA 02169-7471
www.nfpa.org

NIBA—National Industrial Belting Association
Philadelphia, PA 19103
www.niba.org

NIST—National Institute of Standards and Technology
Gaithersburg, MD 20899
www.nist.gov

NLGI—National Lubricating Grease Institute
Kansas City, MO 64112
www.nlgi.com

NSC—National Safety Council
Itasca, IL 60143-3201
www.nsc.org

RMA—Rubber Manufacturers Association
Washington, DC 20005
www.rma.org

RSA—Robotics Society of America
www.robotics-society.org

SAE—Society of Automotive Engineers
Warrendale, PA 15096
www.sae.org

SME—Society of Manufacturing Engineers
Dearborn, MI 48128
www.sme.org

SMI—Spring Manufacturers Institute
Oak Brook, IL 60523-1335
www.smihq.org

UL—Underwriters Laboratories, Inc.
Northbrook, IL 60062-2069
www.ul.com

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Societies, Associations, Institutes, and Specification Authorities

16.2 Quality-Control Systems

Various standards for controlling the quality of industrial and consumer products have been implemented both nationally and internationally. These standards are important to manufacturers, product design engineers, and engineering departments. In the United States, a system known as *total quality management* (TQM) has been in effect for some years. Other quality-control systems have been implemented nationally and on a company-level basis. These systems help the consumer as well as the manufacturer.

Internationally, the quality-control or quality-assurance system of most importance to American manufacturers is the International Standards Organization (ISO) 9000 system. On January 1, 1993, the European Community (EC), consisting of 12 countries, officially formed a unified market. This began the adoption of the ISO 9000 system. All U.S. companies wishing to sell products to the European market will use the ISO 9000 system as their quality standard.

ISO 9000 establishes a minimum quality standard that may be expanded on, based on future requirements. The U.S. Department of Defense may replace standards MIL-I-45208A and MIL-Q-9858A with the ISO 9000 system. After January 1, 1993, U.S. companies may be required to be in compliance with ISO 9000 in order to continue to do business with the EC nations. Note that the American TQM system will exceed the stated ISO 9000 guidelines. Sixty countries have adopted ISO 9000 as their national quality standard.

The EC Consumer Council Ministers have adopted a general product safety directive. This directive imposes general safety requirements on all consumer products sold in the EC market. U.S. exporters to the EC must familiarize themselves with the EC product liability regulations. Use of the ISO 9000 standard may be mandatory in the near future in order for U.S. companies to sell their products to the EC and other nations that have adopted the ISO 9000 standard.

16.3 ISO 9000 System

The ISO 9000 system is divided into a series of standards, including

- ISO 9001—model for quality assurance in design and development, production, installation, and servicing
- ISO 9002—model for quality assurance in production and installation

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- ISO 9003—model for quality assurance in final inspection and test
- ISO 9004—guidelines to quality management elements

ISO 9001, 9002, and 9003 are audited quality-control standards, whereas ISO 9004 contains the guidelines to quality management elements and is not audited. The ISO standard your company may require depends on your manufacturing and product setup.

Additional information on the entire ISO 9000 system may be obtained from the following organizations:

American Society for Quality (ASQ)
Milwaukee, WI 53203
(800) 248-1946
www.asq.org

National Technical Information Service (NTIS)
Springfield, VA 22161
(703) 605-6000
www.ntis.gov

U.S. Government Printing Office (GPO)
Washington, DC 20402
(202) 783-3238
www.gpo.gov

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Chapter

17

American National Standards Applicable to Machinery, Machining, and Metalworking Practices

The American National Standards Institute (ANSI) issues standards in the form of published pamphlets that define the geometry, dimensions, inspection limits, test procedures and other control data, and specifications important to the design and manufacture of thousands of items. Components, materials, and specifications such as screw-thread systems, bolts, screws, washers, nuts, splines, pins, cutting tools, mechanical devices, various equipment and machinery, and a host of other items of importance to the machining, metalworking, and mechanical industries are all defined and specified in the various American national standards.

The purpose of these standards is to define the various physical, chemical, electrical, and mechanical characteristics of materials, components, systems, assemblies of equipment, and inspection and testing procedures. The American national standards provide a means for obtaining order and conformity among American manufactured products.

On August 24, 1969, the American Standards Association (ASA) was restructured as the United States of America Standards Institute, and standards that were approved as American standards were designated as USA standards. On October 6, 1969, the name

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American National Standards Applicable to Machinery, Machining, and Metalworking Practices

was then changed to American National Standards Institute (ANSI). The present standards designation is ANSI instead of ASA or USAS.

The American National Standards Institute (ANSI) works in collaboration with other national organizations such as the American Society of Testing and Materials (ASTM), the Society of Automotive Engineers (SAE), the American Welding Society (AWS), the American Society of Mechanical Engineers (ASME), the American Gear Manufacturers Association (AGMA), the American Iron and Steel Institute (AISI), the Institute of Electrical and Electronics Engineers (IEEE), and others in an effort to consolidate the American standards data and publications generated by these other national organizations. The metalworking industries and other industries nationwide depend on the combined national standards of all the various American societies, institutes, and associations in order to have guidelines, specifications, and design and test procedures for manufacturing their products.

Many products and materials are required by purchasing specifications to conform to the various American standards and will not be accepted by a purchaser unless they do conform to the specified standards. For example, when a design engineer specifies a material on his or her design drawing of a spring, the material as listed on the drawing may be 0.156-in-diameter music wire per ASTM-A228.

When the material is delivered to the spring manufacturer, it should conform to the specifications of this standard designation (ASTM-A228) both physically and chemically. If this specified material were to be tested and analyzed at a materials test laboratory, it would be required to conform to the ASTM-A228 specification. Failure of the material to conform to the specification could result in part failure in service.

The designations of the various ANSI standards that are of prime importance to the machining, metalworking, and mechanical industries are listed in this chapter by subject category. It was the author's and publisher's decision to not include extracts of the various ANSI standards in this *Handbook* for the following reasons:

- The basic standards applicable to the machining, metalworking, and mechanical industries are too extensive to republish.
- The standards are being revised constantly to keep pace with changing technologies.
- Whenever a standard is revised, in effect, a handbook containing these standards would be out of date and contain obsolete data.

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Companies that rely on the data contained in the national standards published by ANSI and the other standards organizations should keep copies of the standards that apply to their work in the standards or engineering departments of their organizations. The ANSI standards listed in this chapter are considered by the author to be the main, basic standards required for the machining and metalworking industries. Standards from the ASTM and SAE for materials are extracted in Chap. 4, "Materials and Their Uses."

Most of the national associations, societies, and institutes that generate American standards applicable to the metalworking and electromechanical industries are listed in Chap. 16 of this *Handbook,* together with their current addresses. Standards may be purchased directly from these organizations, and most of the listed organizations have catalogs available that specify the various technical publications they produce.

17.1 Listing of ANSI Standards by Category

1. Thread systems
2. Fastening and joining devices
3. Machining practices
4. Tools and tooling
5. Mechanical components
6. Welding
7. Heat treatment
8. Tolerances and fits
9. Drawing symbols and formats
10. Gauging and inspection

Category 1 : Thread systems

ANSI B1.9-1973, *Buttress Inch Screw Threads*

ANSI B1.10-1958 (R1988), *Unified Miniature Screw Threads*

ANSI B1.1l-1958 (R1989), *Microscope Objective Thread*

ANSI B1.18M-1982 (R1987), *Metric Screw Threads for Commercial Mechanical Fasteners—Boundary Profile Defined*

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ANSI B1.20.3-1976 (R1982), *Dry Seal Pipe Threads (Inch)*

ANSI B1.20.4-1976 (R1982), *Dry Seal Pipe Threads* (metric translation of B1.20.3-1976)

ANSI/ASME B1.1-1989, *Unified Inch Screw Threads (UN and UNR Thread Form)*

ANSI/ASME B1.5-1988, *Acme Screw Threads*

ANSI/ASME B1.7M-1984, *Screw Threads, Definitions and Letter Symbols*

ANSI/ASME B1.8-1988, *Stub Acme Screw Threads*

ANSI/ASME B1.12-1987, *Screw Threads—Class 5 Interference Fit Thread*

ANSI/ASME B1.13M-1983 (R1989), *Metric Screw Threads-M Profile*

ANSI/ASME B1.20.1-1983, *Pipe Threads (General Purpose), Inch*

ANSI/ASME B1.20.7-1966 (R1983), *Hose Coupling Screw Threads*

Category 2: Fastening and joining devices

ANSI B18.1.1-1972 (R1989), *Small Solid Rivets (0.4375 In Diameter and Under)*

ANSI B18.1.2-1972 (R1989), *Large Rivets (0.500 In Diameter and Over)*

ANSI B18.2.1-1981, *Square and Hex Bolts and Screws, Inch Series*

ANSI B18.2.3.1M-1979 (R1989), *Screws, Metric Hex Cap*

ANSI B18.2.3.2M-1979 (R1989), *Screws, Metric Formed Hex*

ANSI B18.2.3.3M-1979 (R1989), *Screws, Metric Heavy Hex*

ANSI B18.2.3.5M-1979 (R1989), *Bolts, Metric Hex*

ANSI B18.2.3.6M-1979 (R1989), *Bolts, Metric Heavy Hex*

ANSI B18.2.3.7M-1979 (R1989), *Bolts, Metric Heavy Hex Structural*

ANSI B18.2.3.8M-1981, *Screws, Metric Hex Lag*

ANSI B18.2.4.1M-1979 (R1989), *Hex Nuts, Style 1, Metric*

ANSI B18.2.4.2M-1979 (R1989), *Hex Nuts, Style 2, Metric*

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ANSI B18.2.4.3M-1979 (R1989), *Hex Nuts, Slotted, Metric*

ANSI B18.2.4.4M-1982, *Nuts, Metric Hex Flange*

ANSI B18.2.4.5M-1979 (R1990), *Hex Jam Nuts, Metric*

ANSI B18.2.4.6M-1979 (R1990), *Hex Nuts, Heavy, Metric*

ANSI B18.5.2.1M-1981, *Bolts, Metric Round Head, Short Square Neck*

ANSI B18.6.1-1981, *Wood Screws, Inch Series*

ANSI B18.6.2-1972 (R1983), *Slotted Head Cap Screws, Square Head Set Screws, and Slotted Headless Set Screws*

ANSI B18.6.3-1972 (R1983), *Slotted and Recessed Head Machine Screws and Machine Screw Nuts*

ANSI B18.6.4-1981, *Screws, Tapping and Metallic Drive, Inch Series, Thread Forming and Cutting*

ANSI B18.7-1972 (R1980), *Semitubular Rivets, Full Tubular Rivets, Split Rivets, and Rivet Caps, General Purpose*

ANSI B18.8.1-1972 (R1983), *Clevis Pins and Cotter Pins*

ANSI B18.8.2-1978 (R1989), *Pins-Taper Pins, Dowel Pins, Straight Pins, Grooved Pins, and Spring Pins, Inch Series*

ANSI B18.9-1958 (R1989), *Plow Bolts*

ANSI B18.11-1961 (R1983), *Miniature Screws*

ANSI B18.17-1968 (R1983), *Wing Nuts, Thumb Screws, and Wing Screws*

ANSI B18.22M-1981, *Washers, Metric Plain*

ANSI B18.22.1-1965 (R198I), *Plain Washers*

ANSI/ASME B18.1.3M-1983 (RI989), *Metric Small Solid Rivets*

ANSI/ASME B18.2.2-1987, *Square and Hex Nuts, Inch Series*

ANSI/ASME B18.2.3.4M-1984, *Screws, Metric Hex Flange*

ANSI/ASME B18.2.3.9M-1984, *Metric Heavy Hex Flange Screws*

ANSI/ASME B18.3-1986, *Socket Cap, Shoulder and Set Screws, Inch Series*

ANSI/ASME B18.3.1M-1986, *Screws, Socket Head Cap, Metric Series*

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American National Standards Applicable to Machinery, Machining, and Metalworking Practices

ANSI/ASME B18.3.3M-1986, *Hexagon Socket Head Shoulder Screws, Metric Series*

ANSI/ASME B18.3.4M-1986, *Screws, Hexagon Socket Button Head Cap, Metric*

ANSI/ASME B18.3.5M-1986, *Hexagon Socket Flat Countersunk Head Cap Screws, Metric Series*

ANSI/ASME B18.3.6M-1986, *Screws, Hexagon Socket Set, Metric Series*

ANSI/ASME B18.5.2.2M-1982, *Bolts, Metric Round Head Square Neck*

ANSI/ASME B18.6.5M-1986, *Metric Thread Forming and Thread Cutting Tapping Screws*

ANSI/ASME B18.6.7M-1985, *Metric Machine Screws*

ANSI/ASME B18.13-1987, *Screw and Washer Assemblies, SEMs, Inch Series*

ANSI/ASME B18.15-1985, *Forged Eyebolts*

ANSI/ASME B18.21.1-1990, *Lock Washers*

ANSI/ASME B18.21.2M-1990, *Lock Washers, Metric Series*

Category 3: Machining

ANSI B5.8-1972 (R1988), *Chucks and Chuck Jaws*

ANSI B5.10-1981 (R1987), *Machine Tapers*

ANSI B5.16-1952 (R1986), *Accuracy of Engine and Tool Room Lathes*

ANSI B17.1-1967 (R1989), *Keys and Keyseats*

ANSI B17.2-1967 (R1978), Woodruff Keys and Keyseats

ANSI B74.2-1982, *Shapes and Sizes of Grinding Wheels and Shapes, Sizes, and Identification of Mounted Wheels, Specifications for*

ANSI B74.13-1990, *Markings for Identifying Grinding Wheels and Other Bonded Abrasives*

ANSI B94.2-1983 (R1988), *Reamers*

ANSI B94.3-1965 (R1984), *Straight Cutoff Blades for Lathes and Screw Machines*

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American National Standards Applicable to Machinery, Machining, and Metalworking Practices

ANSI B94.7-1980 (R1987), *Hobs*

ANSI B94.8-1967 (R1987), *Inserted Blade Milling Cutter Bodies*

ANSI B94.llM-1979 (R1987), *Twist Drills, Straight Shank and Taper Shank Combined Drills and Countersinks*

ANSI B94.21-1986 (R1987), *Gear Shaper Cutters*

ANSI B94.49-1975 (R1986), *Spade Drill Blades and Spade Drill Holders*

ANSI/ASME B5.1M-1985, *T-Slots—Their Bolts, Nuts, and Tongues*

ANSI/ASME B94.6-1984, *Knurling*

ANSI/ASME B94.9-1987, *Taps, Cut and Ground Threads*

ANSI/ASME B94.19-1985, *Milling Cutters and End Mills*

Category 4: Tools and tooling accessories

ANSI B5.25-1978 (R1986), *Punch and Die Sets, Inch*

ANSI B5.25M-1980 (R1986), *Punch and Die Sets, Metric*

ANSI B94.14-1968 (R1987), *Punches—Basic Head Type*

ANSI B94.14.1-1977 (R1984), *Punches—Basic Head Type, Metric*

ANSI B94.33-1974 (R1986), *Jig Bushings*

ANSI B107.6-1978 (R1987), *Box, Open End, Combination and Flare Nut Wrenches, Inch Series*

ANSI B107.9-1978 (R1987), *Box, Open End, Combination and Flare Nut Wrenches, Metric Series*

ANSI B107.10M-1982 (R1988), *Socket Wrenches, Handles and Attachments for Hand, Inch and Metric Series*

ANSI/ASME B107.5M-1987, *Socket Wrenches, Hand, Metric*

ANSI/ASME B107.8M-1984, *Adjustable Wrenches*

ANSI/ASME B107.19-1987, *Pliers, Retaining Ring*

Category 5: Mechanical components

ANSI B29.2M-1982 (R1987), *Inverted Tooth (Silent) Chains and Sprockets*

ANSI B29.6M-1983 (R1988), *Steel Detachable Link Chains and Sprockets*

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American National Standards Applicable to Machinery, Machining, and Metalworking Practices

ANSI B29.10M-1981 (R1987), *Heavy Duty Offset Sidebar Transmission Roller Chains and Sprocket Teeth*

ANSI B29.15-1973 (R1987), *Heavy Duty Roller Type Conveyor Chains and Sprocket Teeth*

ANSI B29.19-1976 (R1987), *A and CA550 and 620 Roller Chains, Attachments and Sprockets*

ANSI B92.1-1970 (R1982), *Involute Splines and Inspection, Inch Version*

ANSI B92.2M-1981 (R1989), *Involute Splines, Metric Module*

ANSI/ASME B29.1M-1986, *Precision Power Transmission Roller Chains, Attachments and Sprockets*

Category 6: Welding

ANSI/AWS D9.1-90, *Sheet Metal Welding Code*

ANSI/AWS D10.12-89, *Recommended Practices and Procedures for Welding Low-Carbon Steels*

ANSI/AWS D11.2-89, *Guide for Welding Iron Castings*

ANSI/AWS D14.2-86, *Machine Tool Weldments, Specification for Metal Cutting*

Category 7: Heat treatment

ANSI/SAE AMS 2728, *Heat Treatment of Wrought Copper Beryllium Alloy Parts*

ANSI/SAE AMS 2756, *Gas Nitriding of Steel Parts*

ANSI/SAE AMS 2757, *Gaseous Nitrocarburizing*

ANSI/SAE AMS 2759, *Heat Treatment of Steel Parts, General Requirements*

ANSI/SAE AMS 2759/3, *Heat Treatment of Precipitation Corrosion Resisting and Maraging Steel Parts*

ANSI/SAE AMS 2759/4, *Heat Treatment of Austenitic Corrosion Resistant Steel Parts*

ANSI/SAE AMS 2759/5, *Heat Treatment of Martensitic Corrosion Resistant Steel Parts*

ANSI/SAE AMS 2759/6, *Heat Treatment and Gas Nitriding of Low-Alloy Steel Parts*

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American National Standards Applicable to Machinery, Machining, and Metalworking Practices

ANSI/SAE AMS 2760A, *Heat Treatment-Carbon, Low-Alloy, and Specialty Steels*

ANSI/SAE AMS 2770D, *Heat Treatment of Aluminum Alloy Parts*

ANSI/SAE AMS 2775A, *Case Hardening of Titanium and Titanium Alloys*

Category 8: Tolerances and fits

ANSI B4.1-1967 (R1987), *Preferred Limits and Fits for Cylindrical Parts*

ANSI B4.2-1978 (R1984), *Preferred Metric Limits and Fits*

ANSI B4.3-1978 (R1984), *General Tolerances for Metric Dimensioned Products*

ANSI B89.3.1-1972 (R1988), *Out-of-Roundness, Measurement of*

ANSI B89.6.2-1973 (R1988), *Temperature and Humidity Environment for Dimensional Measurement*

ANSI Y14.5M-1982 (R1988), *Dimensioning and Tolerancing*

ANSI/ASME B1.22M-1985, *Gauges and Gauging Practice for MJ Series Metric Screw Threads*

ANSI/ASME B107.17M-1985, *Gauges, Wrench Openings, Reference*

Category 9: Drawing symbols and formats

ANSI Y10.20-1975 (R1988), *Mathematic Signs and Symbols for Use in Physical Sciences and Technology*

ANSI Y14.1-1980 (R1987), *Drawing Sheet Size and Format*

ANSI Y14.7.1-1971 (R1988), *Gear Drawing Standards, Part 1: For Spur, Helical, Double Helical, and Rack*

ANSI Y14.7.2-1978 (R1989), *Gear and Spline Drawing Standards, Part 2: Bevel and Hypoid Gears*

ANSI Y14.17-1966 (R1987), *Fluid Power Diagrams*

ANSI Y14.36-1978 (R1987), *Surface Texture Symbols*

ANSI Y32.10-1967 (R1987), *Graphic Symbols for Fluid Power Diagrams*

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Category 10: Gaging and inspection

ANSI B4.4M-1981 (R1987), *Inspection of Work Pieces*

ANSI B89.3.1-1972 (R1988), *Out-of-Roundness, Measurement of*

ANSI/ASME B1.2-1983, *Gauges and Gauging for Unified Screw Threads*

ANSI/ASME B1.3M-1986, *Gauging Systems for Dimensional Acceptability, Inch and Metric Screw Threads (UN, UNR, UNJ, M, and MJ)*

ANSI/ASME B1.16M-1984, *Gauges and Gauging for Metric M Screw Threads*

ANSI/ASME B1.19M-1984, *Gauges for Metric Screw Threads for Commercial Mechanical Fasteners—Boundary Profile Defined*

ANSI/ASME B107.17M-1985, *Gauges, Wrench Openings, Reference*

17.2 Standards and Approval Agencies and Acronyms

AEC	Atomic Energy Commission
AGA	American Gas Association
AGMA	American Gear Manufacturers Association
AHAM	Association of Home Appliance Manufacturers
AMCA	Air Movement and Control Association
AN	Army-Navy Standard
ANSI	American National Standards Institute
ARA	American Refrigeration Association
ARL	Applied Research Laboratories
ASA	American Standards Association (Now ANSI)
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASSE	American Society of Sanitary Engineering
CEC	California Energy Commission
CGA	Canadian Gas Association

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CSA	Canadian Standards Association
DIN	Deutschland Ingineering Normalization (German Engineering/Industrial Standard)
DOT	Department of Transportation
ETL	ETL Testing Laboratories
FM	Factory Mutual
FSEC	Florida Solar Energy Center
GAMA	Gas Appliance Manufacturers Association
HVI	Home Ventilating Institute
IAPMO	International Association of Plumbing and Mechanical Officials
IEC	International Electrotechnical Commission
ISO	International Standards Organization
JAN	Joint Army-Navy Standard
MS	Military Standard
NASA	National Aeronautics and Space Administration
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NSF	National Sanitation Foundation
OPEI	Outdoor Power Equipment Institute
OSHA	Occupational Safety and Health Administration
SRCC	Solar Rating and Certification Corporation
UL	Underwriters' Laboratories
USAS	USA Standard (Now ANSI)
USDA	United States Department of Agriculture

17.3 Approval Associations and Their Trademarks

See Fig. 17.1.

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American National Standards Applicable to Machinery, Machining, and Metalworking Practices

AGA American Gas Association
AGMA American Gear Manufacturer's Assn.
AHAM Association of Home Appliance Manufacturers
AMCA Air Movement and Control Association
ANSI American National Standards Institute
ARI Air-Conditioning & Refrigeration Institute
ARL Applied Research Laboratories
ASHRAE American Society of Heating, Refrigerating, and Air-conditioning Engineers
ASME American Society of Mechanical Engineers
ASSE — American Society of Sanitary Engineering
CGA Canadian Gas Association
CSA Canadian Standards Association
CSA Canadian Standards Association, National Recognized Testing Laboratory
NRTL
CE Conformité Européenne
DIN Deutschland Ingineering Normalization
DOT Department of Transportation
ETL ETL Testing Laboratories
FM Factory Mutual
GAMA Gas Appliance Manufacturers' Association
HVI Home Ventilating Institute
IAPMO International Association of Plumbing and Mechanical Officials
ISO International Organization for Standardization
NEC National Electrical Code
NEMA — National Electrical Manufacturers Association
NFPA National Fire Protection Association
NSF National Sanitation Foundation Internation
OPEI Outdoor Power Equipment Institute
OSHA Occupational Safety and Health Administration
SAE Society of Automotive Engineers
SRCC Solar Rating and Certification Corporation
SSPMA Sump and Sewage Pump Manufacturers Association
UL Underwriters Laboratories (Recognized Component Mark)
UL Underwriters Laboratories (Recognized Component Mark for Canada)
UL Underwriters Laboratories
UL Underwriters Laboratories (Listing Mark Canada)
UL Underwriters Laboratories (Listing Mark Classified products)
USDA United States Department of Agriculture

Figure 17.1 Trademarks of approval associations.

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